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WIND TUNNEL MEASUREMENT AND ASSESSMENT ON THE PEDESTRIAN WIND ENVIRONMENT – A CASE STUDY OF JINYING HIGH RISE BUILDING IN TAIPEI, TAIWAN

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ABSTRACT

In this paper, wind tunnel measurement study on the pedestrian level (1.5 m to 2 m height from the ground) wind environment was carried out and applied to a case measurement of JinYing high-rise building of a height of 86.8 m in Taipei, Taiwan. Wind tunnel measurements incorporating with statistical analysis of in-situ recorded wind data were applied to asses the wind environment of pedestrian level wind comfort and safety due to the JinYing building project. Long term in-situ recorded wind data in the nearby of the high-rise building site was collected and analyzed. The Weibull probability distribution was found to fit better for the wind speed data. For each location around the JinYin building, we integrated the measured wind tunnel pedestrian level peak wind speed and Weibull probability distribution of the wind speed to yield the results for assessing the pedestrian level wind comfort and safety around the building. Based on the pedestrian level wind acceptability criteria proposed by the RWDI company in Canada, it is concluded the comfort and safety of pedestrian level activities are acceptable of the JinYing high rise building project. Also the present study offered an example for assessing how the high-rise building project affects the local wind environment experienced by pedestrian activities both to ensure comfort or safety and to facilitate the attractiveness of the building project.

Keywords: wind tunnel, pedestrian wind, wind rose diagram, Weibull probability distribution

INTRODUCTION

Due to the vast increase of commercial and living activities in heavy city, large and high-rise buildings are built intensively. The wind environment around the large or high-rise buildings has become an important issue of engineering and environment. The pedestrian level wind is one of most concerned wind environment problems. The change in pedestrian wind due to the newly built building may cause uncomfortable and dangerous impacts on the people activities (such as walk, sit, stroll, or stay) around the building. Therefore, it is necessary to evaluate the situation of pedestrian wind environment for the building project.

Recently, there have been progressive studies on the pedestrian level winds. Stathopoulos (2006) established an approach for an overall comfort index of pedestrian winds. Bu *et al.* (2009) made new

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criteria for assessing local wind environment at pedestrian level which was based on exceedance probability analysis. Sanz-Andres and Cuerva (2006) investigated the feasibility study of criteria homogenization for pedestrian wind comfort. Visser *et al.* (2000) developed a “KnoWind” model which is a database-oriented approach and can determine the pedestrian level wind environment around buildings. In this study we carried out the wind tunnel measurement on the pedestrian level wind around the JinYing high-rise building with height of 86.8 m in Taipei, Taiwan. The measurements incorporating with statistical analysis of in-situ micrometeorological data (wind speed and direction data) offer the wind environment assessment of pedestrian level wind comfort and safety due to the building project. Long term of in-situ hourly recorded wind data in the nearby of the high-rise building site was collected and analyzed. The Weibull probability distribution was applied to fit of the wind data. For each location around the building, we integrate measured wind tunnel pedestrian level wind speed and the statistical analysis of the wind climate data to yield the indicators for assessment of the wind comfort and safety around the building. Results will help to know and assess how the high-rise building project affects the local wind environment experienced by pedestrians both to ensure comfort or safety and to facilitate the attractiveness of the building project.

EXPERIMENTAL SETUP OF WIND TUNNEL

The measurements were conducted in the National Taiwan Ocean University’s Environmental Wind Tunnel. The wind tunnel test section has a cross section of 2 m wide by 1.4 m high, and 12.5 m long. The tunnel is an open suction type and it contracts to the test section with an area ratio of 4:1. The turbulence intensity of empty tunnel in test section is less than 0.5 % at the mean velocity of 5 m/s.

Four spires of 100 cm height and cubic elements (5 cm x 5 cm x 5cm) are properly arranged as the roughness at the entrance of test section to generate a thick turbulent boundary layer which is used as the approaching flow. An X-type hot-wire incorporating with the TSI IFA-300 constant temperature anemometer was employed to measure the turbulent flow signals. Output of the analog signals for turbulent flow was digitized at a rate of 4k Hz each channel through the 12 bit Analog-to–Digital converter. Since none of the analog signals containing significant energy or noise above 1k Hz, with the Nyquist criteria, a digitizing rate of 2k Hz was sufficient. The low pass frequency for the analog signals is set as 1k Hz in the experiments. The pedestrian level wind speed was measured by using Irwin probe (Irwin(1981)). As indicated by Durgin (1992), Irwin probe is adequate for application in measuring pedestrian level wind speed. It is provided that an adequate and not too great frequency response for the pressure sensing system is employed with the Irwin probe.

The model scale used in the wind tunnel test is 1/400. Geometric and dynamic similarity requirements were employed to simulate the neutral turbulent boundary layer flow in urban area which is used as the approaching flow. The free stream velocity is 9 m/s, and boundary layer thickness 100 cm. The Reynolds number in the experiments was about 8.4×10^5. This ensures the Reynolds number similarity of flow between the model and prototype. The full scale of the building height is 86.8 m. And the building site area is 5276 m^2. Fig.1 shows the JinYing building model arrangement in the wind tunnel. And Fig.2 is the measurement location label of pedestrian level wind around the building.

PROBABILITY ANALYSIS OF IN-SITU MEASURED WIND DATA

The in-situ measured wind data were collected for eleven years from Taipei meteorological station (No.46692), Central Weather Bureau, Taiwan. The wind data was recorded hourly. To analyze the wind data, the Weibull probability density function is adopted. The probability distribution for in-situ measured wind data is fit as,

$$P(U;c,k) = \frac{k}{c}(\frac{U}{c})^{k-1} \exp[-(\frac{U}{c})^{k}] \tag{1}$$

where the c is the scaling factor, and k is the shape factor. And U is the mean wind speed.

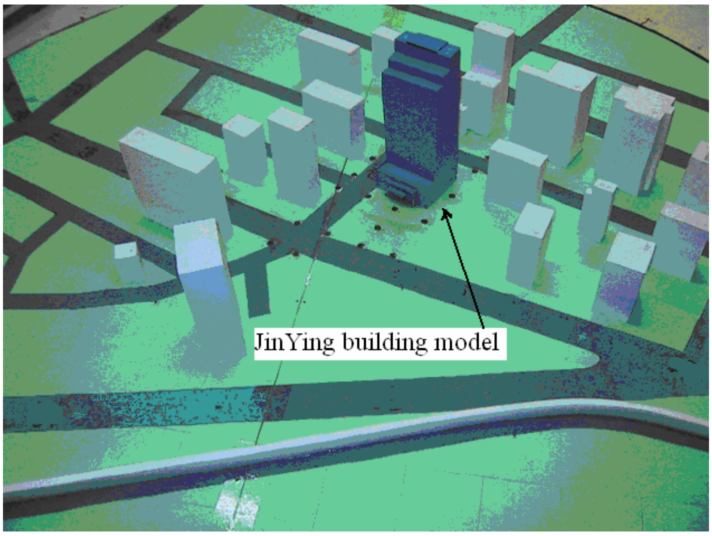

Fig. 1. Main building model arrangement in wind tunnel

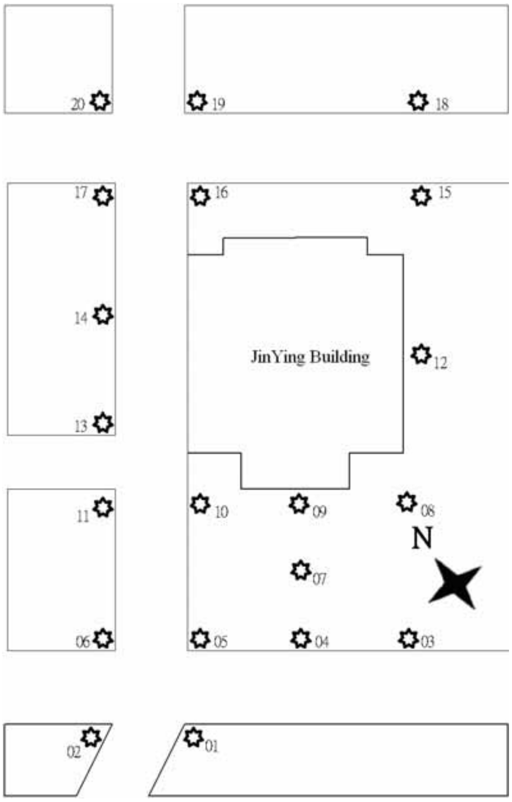

Fig. 2. Label of measurement location for pedestrian level wind

The cumulative probability distribution of wind occurrence probability in *i-th* wind direction for wind speed less and equal U is expressed as:

$$P_i(speed \le U) = 1 - \exp[-(\frac{U}{c_i})^{k_i}] \tag{2}$$

The total wind occurrence probability for wind speed less and equal U is the summation of all sixteen wind directions, and can be expressed as:

$$P(speed \le U) = \sum_{i=1}^{16} w_i \{1 - \exp[-(\frac{U}{c_i})^{k_i}]\} \tag{3}$$

where the w_i represents wind occurrence percentage for wind direction i.

RESULTS

Approaching Flow

The turbulent boundary layer flow was generated as the approaching flow. Mean velocity profile of the simulated turbulent boundary layer flow is approximated by the power law shown as equation (4).

$$\frac{U(Z)}{U_{ref}} = (\frac{Z}{Z_{ref}})^n \tag{4}$$

where $U(Z)$ is the mean velocity at height of Z , U_{ref} is the free stream velocity, and Z_{ref} is the boundary layer thickness. The free stream velocity is U_{ref} =9 m/s; and the boundary layer thickness, Z_{ref} is about 100 cm. The measured mean velocity profile is shown in Fig. 3. Results indicate that the mean velocity profile expressed in power law is with a power exponent, n=0.24. Counihan (1975) indicated the power index range 0.23~0.40 for urban area. The present simulation of approaching flow fit to the power index range for terrain type of urban area as indication of Counihan (1975).

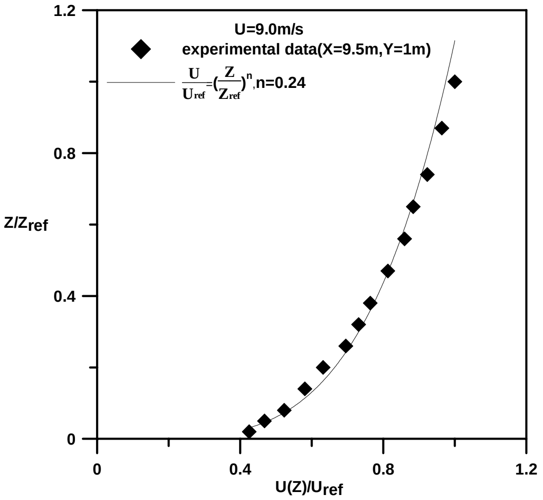

Fig. 3. The mean velocity profile of approaching flow

The simulated longitudinal turbulence intensity profile of approaching flow is shown in Fig. 4. Fig. 4 shows the simulated longitudinal turbulence intensity of approaching flow increases with decreasing the height. As the height close to the ground, the longitudinal turbulence intensity exceeds 20 % and approaches to about 25%. Counihan (1975) summarized that the longitudinal turbulence intensity for heights 2~30 m above ground level for rural area fell in the range of 0.2 to 0.35.

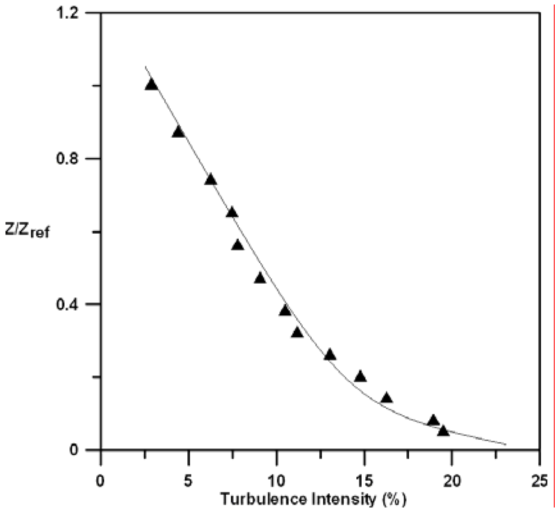

Fig. 4. The longitudinal turbulence intensity of approaching flow

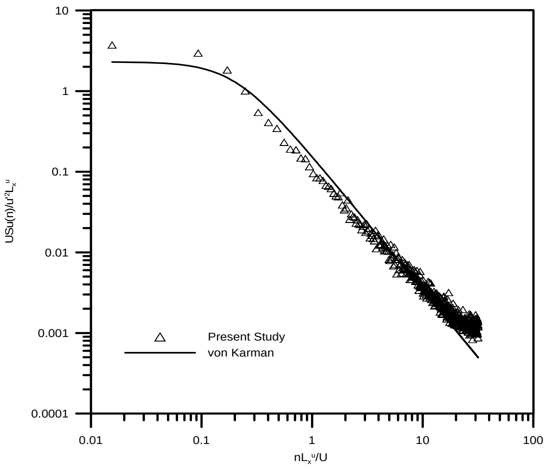

Fig. 5. The turbulence power spectrum of approaching flow at Z/Z_{ref}=0.2

Fig. 5 shows the turbulence power spectrum of approaching flow measured at Z/Z_{ref}=0.2. Maeda and Makino (1988) rewrote the Von-Karman type power spectrum equation as follows:

$$S_u(n)=\frac{2u^{'}L^{u_x}}{U[1+(\frac{2cnL^{u_x}}{U})^2]^{\frac{5}{6}}} \qquad (5)$$

In Fig. 5, the spectrum density, $S_u(n)$ and frequency, n are normalized, and they are denoted by

$US_u(n)/u'L^{u_x}$ and nL^{u_x}/U, respectively. Here u' denotes the mean square of longitudinal velocity fluctuation, $\overline{u^2}$; c is coefficient of 4.2065; L^{u_x} is the integral length scale of longitudinal velocity in x direction; U is the longitudinal mean velocity at the height of z. The integral length scale is obtained by multiplying the integral time scale, T_E with the longitudinal mean velocity, U. The integral time scale, T_E is computed by integrating the longitudinal velocity autocorrelation coefficient function, $R_u(\tau)$.

The Von-Karman type power spectrum equation is also plotted and shown in the Fig. 5 for comparison. It is found that a satisfactory agreement is achieved for the inertia-subrange of turbulent approaching flow structure simulation.

Pedestrian Level Wind

In the model study, pedestrian level winds of 20 locations around the building for sixteen wind direction cases were measured including the mean wind speed, U and peak wind speed, U_G.

Results of the mean wind speed are listed in Table 1. The mean wind speed shown in the table is scaled with the free stream velocity, i.e. U/U_{ref} (%). The free stream velocity U_{ref} is 9 m/s. In the front face region of building, there is a plaza. In the building front face area, we measured locations labeled such as: 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, and 11. Results listed in Table 1 show that the mean speed of pedestrian wind at these locations are all smaller than free stream velocity (i.e. < 100 %). The mean speeds of pedestrian wind at the plaza center (location 7) are greater than that of at other locations (like locations 3, 4, 5, 8, 9, 10) for all wind directions. On the leeside area of building, the mean speed of pedestrian wind at locations 15, 16, 17, 18, 19, 20 are all smaller than free stream velocity (i.e. < 100 %) for all wind directions. The mean speed of pedestrian wind at left hand side area of building (location 12) is higher than that of at the right hand side area of building (location 13, 14). The pedestrian level winds around the building under wind action with different directions are shown here by the wind rose diagram for convenience. As an example, the wind rose diagram of mean wind speed of pedestrian level wind as examples at locations 7 and 15 are shown in Fig.6. In the figure, the mean wind speed is scaled with the free stream velocity, i.e. U/U_{ref} (%). As comparing pedestrian level wind for these two locations, we find that the mean wind speeds of pedestrian level at location 7 are greater than that of location 15 in all wind directions.

The peak wind speed is also an important index of assessment on comfort and safety for the pedestrian wind environment. The peak wind speed, U_G employed here is defined as:

$$U_G = U + k \cdot u_{rms} \tag{6}$$

where gust factor k = 3.0 (Hunt *et al*, (1976)); U is the mean wind speed; u_{rms} is the root mean square of wind speed fluctuation. The peak wind speed is scaled with the free stream velocity, i.e. U/U_{ref} (%). The free stream velocity U_{ref} is 9 m/s. Results of the scaled peak wind speed at locations around building under action of different wind directions are shown in Table 2. Results of measured locations in the front face region of building (labeled such as: 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, and 11) show that the peak wind speed of pedestrian wind at these locations are all smaller than free stream velocity (i.e. < 100 %). The peak wind speed at location 7 in the center of plaza are greater than that of at the other measured locations in these area, such as 3, 4, 5, 8, 9, 10. The measured peak wind speeds at location 12 on left hand side of building are higher than that of locations 13, and 14 on the right hand side of building under the action of wind directions of N, NNE, NE, ENE, E, ESE, SE, SW, WNW, and NW. On the leeside region of the building, the peak wind speed at location 20 exhibits higher value under the action of southern wind. This is due to the corner wind effect when southern wind flows over the building.

Table 1. Mean speed of pedestrian level winds around the building for different wind directions

	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WW	W	WW	NW	NNW
1	65.79	40.7	35.57	35.51	37.95	44.52	49.03	39.36	41.12	41.81	54.38	37.53	36.85	44.13	48.34	63.99
2	70.10	50.29	35.69	39.2	38.82	44.49	49.33	41.52	43.75	54.01	55.24	35.44	33.23	46.03	57.09	68.67
3	37.66	31.61	33.13	35.93	31.83	37.18	47.26	42.14	30.70	42.59	36.97	39.93	38.97	37.64	43.44	48.07
4	42.37	32.56	32.01	36.79	32.30	39.79	46.35	39.68	34.10	41.41	42.60	40.09	39.95	38.74	44.11	46.82
5	50.29	39.34	34.52	40.14	31.91	37.94	42.40	39.02	34.94	34.35	39.52	36.02	38.17	35.97	38.44	41.03
6	59.86	53.38	51.9	61.95	55.95	64.84	67.51	49.29	54.68	53.05	53.54	35.11	42.06	44.09	51.65	55.15
7	64.31	61.26	59.94	63.00	59.87	60.33	66.13	63.44	57.73	60.40	60.63	64.55	61.81	65.23	73.23	76.41
8	40.62	38.65	37.93	39.12	41.23	37.49	37.48	34.40	33.00	37.13	38.01	46.43	47.17	42.02	39.16	37.25
9	42.85	35.69	37.71	40.76	31.12	33.27	37.49	39.69	31.76	33.50	30.27	43.90	47.37	47.18	45.91	48.72
10	54.83	41.92	37.77	37.04	29.68	34.42	44.06	49.91	43.77	48.46	41.78	48.32	49.25	57.57	69.77	63.74
11	52.29	38.29	42.29	42.10	42.55	43.42	57.87	57.17	57.96	52.81	43.43	37.32	40.76	46.94	44.11	53.47
12	47.59	48.39	50.81	52.53	38.69	37.65	52.46	54.45	53.86	54.70	47.20	35.74	34.95	40.55	40.20	34.62
13	37.57	37.76	41.04	41.61	31.7	31.74	31.29	35.84	36.69	41.45	39.43	46.73	37.23	31.85	35.34	45.39
14	39.93	45.68	49.89	53.38	42.19	32.63	44.47	63.59	58.14	59.59	44.87	38.23	31.05	40.28	37.16	34.10
15	39.93	36.96	32.7	31.54	30.85	40.49	43.58	41.43	39.84	45.75	40.12	36.94	37.57	36.82	38.16	40.29
16	57.13	57.96	58.25	61.32	58.13	58.66	62.39	64.44	57.45	53.01	48.41	57.59	58.73	52.55	50.87	52.07
17	56.28	61.55	67.7	64.20	58.81	57.70	60.62	73.58	74.25	75.71	61.92	58.69	55.48	57.61	59.59	55.69
18	42.54	47.08	48.3	37.93	29.00	29.60	35.33	37.50	38.84	39.11	37.71	42.30	41.97	39.75	41.18	41.36
19	46.06	46.11	41.03	43.07	34.96	35.54	44.43	41.02	38.53	39.26	46.03	50.33	50.71	42.05	38.85	47.12
20	37.01	44.99	53.72	47.20	35.84	34.02	37.93	43.26	66.21	53.15	50.29	46.34	53.21	48.12	39.89	31.68

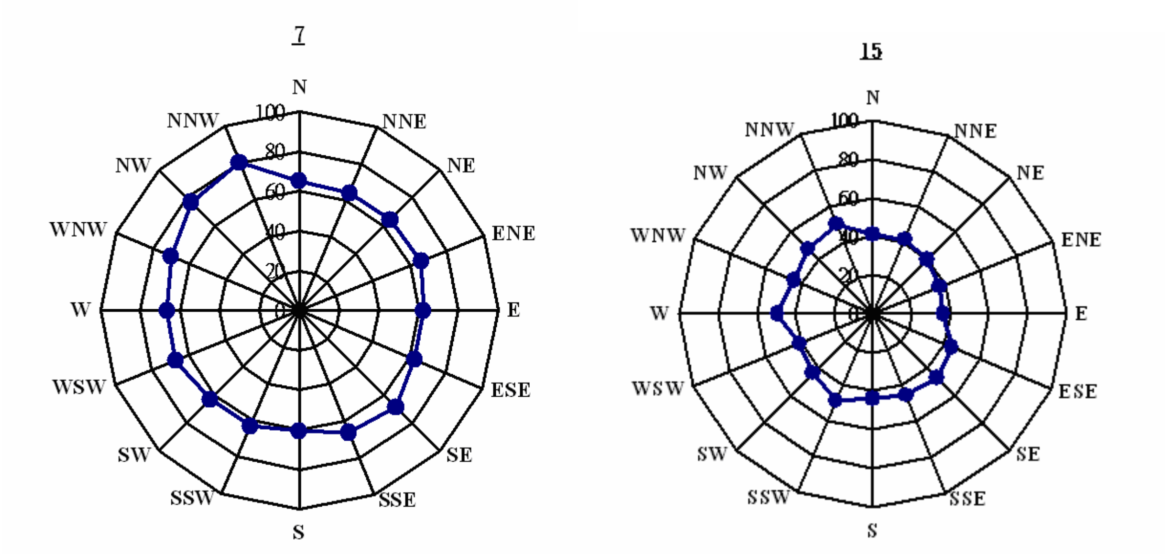

Fig. 6. The wind rose diagram for mean wind speed of pedestrian level wind at location 7 and 15

Table 2. Peak speed of pedestrian level winds around the building for different wind directions

	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW
1	67.03	47.95	44.74	42.41	43.92	47.70	52.22	43.67	44.91	46.08	57.4	41.42	41.84	50.83	53.92	67.03
2	71.01	54.35	47.79	44.48	43.23	47.78	52.41	45.32	47.5	56.88	58.03	39.76	39.49	52.95	62.23	71.58
3	39.17	38.02	41.38	41.28	37.39	41.15	50.55	45.72	35.93	46.32	41.33	44.02	43.03	48.18	47.91	51.53
4	43.87	38.94	40.56	42.07	37.60	43.74	50.11	44.03	38.94	45.54	46.5	43.69	46.98	44.77	48.29	53.26
5	67.03	44.17	42.57	44.29	37.77	41.95	46.54	43.49	40.27	38.89	43.49	40.27	44.31	43.31	43.20	52.90
6	60.77	57.37	57.20	65.11	58.73	67.07	69.86	53.03	58.19	56.25	56.44	39.43	46.4	50.31	56.78	60.16
7	65.10	64.34	64.52	66.03	62.39	62.88	68.73	66.19	60.52	63.15	63.12	67.03	66.63	69.94	76.91	80.34
8	41.94	43.69	44.95	44.08	45.14	41.39	42.21	39.76	38.1	41.38	42.02	50.14	50.79	49.47	45.15	44.77
9	44.14	40.11	42.50	45.01	35.72	37.80	41.82	43.66	37.61	37.71	35.22	47.39	51.72	52.39	51.40	54.95
10	55.73	46.50	43.15	42.13	34.83	39.18	47.35	54.09	47.88	51.59	45.42	51.65	55.93	61.07	73.56	68.01
11	53.31	42.43	46.65	46.36	46.63	46.87	60.66	60.04	61.31	55.60	47.10	41.44	47.96	51.55	49.64	57.92
12	48.62	51.88	55.06	56.95	42.75	41.62	55.61	57.34	57.10	57.26	50.66	39.99	42.24	47.34	47.92	40.32
13	38.78	42.53	45.78	46.32	36.87	36.66	36.26	40.45	41.29	45.04	43.36	49.97	44.37	40.17	44.86	50.46
14	41.03	49.59	53.75	56.83	45.76	37.20	47.86	66.17	61.39	62.13	48.39	41.95	40.05	46.96	46.42	39.74
15	41.08	41.75	39.64	37.27	36.12	44.32	46.76	45.47	44.03	49.02	43.65	41.03	49.48	44.4	47.38	50.03
16	57.92	61.2	62.80	63.92	60.91	61.27	64.81	67.12	60.73	55.77	51.66	60.44	64.51	57.85	57.48	57.42
17	57.62	64.26	71.51	66.70	61.83	60.29	63.3	75.87	76.54	77.79	64.28	61.42	60.62	62.32	64.45	60.91
18	43.66	51.10	52.48	42.38	36.11	34.59	40.01	41.64	42.50	42.96	41.62	46.24	47.82	45.52	46.48	50.20
19	47.11	49.72	45.82	47.83	39.92	39.87	47.98	44.83	42.42	42.84	49.49	53.65	56.01	47.87	45.54	56.01
20	38.37	50.49	57.42	51.36	40.80	38.64	42.06	47.31	68.74	55.87	54.84	49.72	57.75	53.81	47.46	37.25

Assessment and Evaluation on the Comfort and Safety of Pedestrian Level Activities

There had been several pedestrian wind comfort criteria which were suggested to evaluate or assess the comfort and safety of locations around planned building. Ratcliff and Peterka (1990) had made comparison of five pedestrian wind acceptability criteria. The criteria are generally based on the percent time certain wind speeds are exceed annually but differ in implementation. They concluded differences among the criteria are evident. In the present study, we combined the local long term micrometeorological condition with the wind tunnel measurements to analyze the pedestrian level wind environment. The in-situ recorded wind data were analyzed to yield the scale and shape factors of Weibull probability density function for each wind direction. The wind tunnel measured results of pedestrian level wind as shown in Table 2and 3 are incorporated with the cumulative Weibulll probability density function to calculate the probability of pedestrian level wind speed. According to equation (3), the total wind occurrence probability for wind speed less and equal U is the summation of all sixteen wind directions. Calculated results for various pedestrian level peak wind speeds at different locations around the building are shown in Table 3. Results indicate that occurrence probability of peak wind speed less than or equal to 4.7 m/s for most of locations except for locations 6,7,16, and 17, are smaller than 80 %. The occurrence probability of peak wind speed less than or equal to 6.9 m/s exceeds 80 % for all measured locations.

At present, there is no general rule available for the assessment and evaluation of the pedestrian level wind comfort. For the purpose of feasibility and simplicity, the pedestrian level wind acceptability criteria proposed by RWDI consulting company, Canada, were employed in the present study to assess the pedestrian wind comfort and safety. It categorized the wind comfort criteria for different pedestrian activities as: (1) sitting (long time stay): The occurrence probability of peak wind speed less than or equal 4.7 m/s is at least 80%. (2) standing or strolling: The occurrence probability of peak wind speed less than or equal 6.9 m/s is at least 80%.. (3) walking: The occurrence probability of peak wind speed less than or equal 8.9 m/s is at least 80%. (4) Uncomfortable: The occurrence probability of peak wind speed greater than 6.9 m/s exceeds at least 20%. The criteria of safety or dangerous for pedestrian activities is the occurrence frequency of peak wind speed greater than 24.4 m/s exceeds at least 3 times per year. Results shown in Table 3 indicate that pedestrian winds for the locations 6, 7, 16, 17 are acceptable for long time stay or sitting activities. And pedestrian activities of standing or strolling are acceptable for all locations around the building. Uncomfortable or dangerous occurrence possibilities for pedestrian activities seem to be lesser than 20 %. Based on the pedestrian level wind acceptability criteria of RWDI, it is concluded the comfort and safety of pedestrian level activities are acceptable of the JinYing high rise building in Taipei city, Taiwan.

Table 3. Probability of pedestrian level peak wind speed for different locations around the building

Probability (%) / Location	Wind speed ≦4.7 m/s	Wind speed ≦6.9 m/s	Wind speed ≦8.9 m/s	Wind speed ＞8.9 m/s
1	76.78	86.23	87.35	12.65
2	77.85	87.68	88.85	11.15
3	74.56	83.69	84.79	15.21
4	75.16	84.4	85.51	14.49
5	75.71	85.24	86.39	13.61
6	81.68	93.24	94.55	5.45
7	81.96	93.81	95.14	4.86
8	77.99	87.87	89.05	10.95
9	75.54	85.08	86.24	13.76
10	74.62	83.79	84.91	15.09
11	79.30	89.48	90.70	9.30
12	79.50	90.02	91.28	8.717
13	75.54	85.17	86.34	13.66
14	79.56	90.21	91.48	8.519
15	73.00	81.57	82.6	17.40
16	81.95	93.65	94.97	5.03
17	81.96	93.78	95.10	4.90
18	74.04	83.24	84.36	15.64
19	77.70	87.65	88.85	11.15
20	78.44	88.68	89.92	10.08

CONCLUSION

Wind tunnel measurements incorporating with statistical analysis of in-situ recorded wind data were applied to asses the wind environment of pedestrian level wind comfort and safety due to the JinYing building project in Taipei city, Taiwan. Long term in-situ recorded wind data in the nearby of the high-rise building site was collected and analyzed. The Weibull probability distribution was found to fit better for the wind speed data. For each location around the JinYin building, we integrated the measured wind tunnel pedestrian level peak wind speed and Weibull probability distribution of the wind speed to yield the indicators for assessing the pedestrian level wind comfort and safety around the building. Based on the pedestrian level wind acceptability criteria proposed by the RWDI company in Canada, it is concluded the comfort and safety of pedestrian level activities are acceptable of the JinYing high rise building project. Also the present study offered an example for assessing how the high-rise building project affects the local wind environment experienced by pedestrian activities both to ensure comfort or safety and to facilitate the attractiveness of the building project.

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