EXPERIMENTAL SITE WIND AVAILABILITY STUDY FOR SHA TIN, HONG KONG

INVESTIGATION REPORT WWTF017-2009
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Submitted to
Department of Architecture,
The Chinese University of Hong Kong

EXECUTIVE SUMMARY

At the request of the Department of Architecture, The Chinese University of Hong Kong, on behalf of Planning Department of The Government of Hong Kong Special Administrative Region, a study of wind availability and characteristics for a nominated Study Area in Sha Tin was conducted by the CLP Power Wind/Wave Tunnel Facility (WWTF) at The Hong Kong University of Science and Technology, as part of the "Urban Climate Map and Standards for Wind Environment – Feasibility Study". The study was undertaken in accordance with the requirements stipulated in the Australasian Wind Engineering Society Quality Assurance Manual, AWES-QAM-1-2001 (2001) and the American Society of Civil Engineers Manual and Report on Engineering Practice No. 67 for Wind Tunnel Studies of Buildings and Structures (1999). The study was also conducted in accordance with the recommendations of Planning Department's Feasibility Study for Establishment of Air Ventilation Assessment System – Final Report (2005) and Technical Guide for Air Ventilation Assessment for Developments in Hong Kong (2006).

A 1:2000 scale topography study was undertaken to determine the effects of local topography and the surrounding urban environment on mean wind direction, mean wind speed and turbulence intensity at a nominated Study Area in Sha Tin.

A miniature dynamic pressure (Cobra) probe was used to take measurements of the longitudinal, lateral and vertical components of wind speed, at 22.5° increments for the full 360° azimuth, i.e. for sixteen (16) wind directions, and at nine (9) elevations to determine profiles of mean wind speed and turbulence intensity above the Study Area. The results will be used as input boundary conditions for subsequent detailed benchmarking studies. The 1:2000 scale topographical model included the surrounding area up to a distance of up to approximately 10 km from the Study Area.

The topography study results were combined with WWTF's statistical model of the Hong Kong non-typhoon wind climate, based on measurements of non-typhoon winds taken by Hong Kong Observatory at Waglan Island during the period of 1953 – 2006 inclusive, to determine wind roses corresponding to annual and summer mean wind speeds at the Study Area.

In general, the annual prevailing wind characteristics corresponding to non-typhoon winds at an elevation of 500 mPD above the Sha Tin Study Area were similar to the overall characteristics of non-typhoon winds approaching the Hong Kong region, although the magnitudes of the directional wind speeds were reduced. More significant changes were observed at lower elevations due to the combination of buildings and mountains surrounding the Study Area.

The largest reductions in the measured magnitudes of wind speed were mainly caused by the mountains to the south and south-west of the Study Area. The presence of mountains significantly affected the directional characteristics for all wind directions with the highest reductions for the wind directions of 180° 202.5°, 225° and 247.5°. Winds approaching the Study Area from 67.5º were the least affected due to the open sea exposure at Sha Tin Hoi.

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1 INTRODUCTION

At the request of the Department of Architecture, The Chinese University of Hong Kong, on behalf of Planning Department of The Government of Hong Kong Special Administrative Region, a study of wind availability and characteristics was conducted by the CLP Power Wind/Wave Tunnel Facility (WWTF) at The Hong Kong University of Science and Technology for a nominated Study Area in Sha Tin, as part of the "Urban Climate Map and Standards for Wind Environment – Feasibility Study". The study was undertaken in accordance with the requirements stipulated in the Australasian Wind Engineering Society Quality Assurance Manual, AWES-QAM-1-2001 (2001) and the American Society of Civil Engineers Manual and Report on Engineering Practice No. 67 for Wind Tunnel Studies of Buildings and Structures (1999). The study was also conducted in accordance with the recommendations of Planning Department's Feasibility Study for Establishment of Air Ventilation Assessment System – Final Report (2005) and Technical Guide for Air Ventilation Assessment for Developments in Hong Kong (2006).

The Study Area of Sha Tin is centred close to City One Plaza in the Sha Tin District and has a diameter of approximately 1000 m, as shown in Figures 1 and 2. A 1:2000 scale topography study was undertaken to determine the effects of local topography and the surrounding urban environment on mean wind speeds and turbulence intensities at the Study Area. The topography study results were combined with WWTF's statistical model of the Hong Kong non-typhoon wind climate, based on measurements of non-typhoon winds taken by Hong Kong Observatory at Waglan Island during the period of 1953 – 2006 inclusive, to determine site-specific annual and summer wind roses for hourly mean wind speeds.

2 ANALYSIS OF THE HONG KONG WIND CLIMATE

Waglan Island, located approximately 5 km southeast of Hong Kong Island, has been used by Hong Kong Observatory (HKO), formerly The Royal Observatory, Hong Kong, for the collection of long-term wind data since December 1952. Due to its location, relative lack of development over the past 50 years and its generally uninterrupted exposure to winds, data collected at Waglan Island is considered to be of the highest quality available for wind engineering purposes in Hong Kong and representative of winds approaching the Hong Kong region. Wind speed and direction measurements at Waglan Island are essentially free from the interference effects of nearby developments and they can be position corrected to account for the effects of the location and height of the anemometer stations and the effects of the surrounding topography and buildings.

Waglan Island wind records have been analysed previously in studies of the Hong Kong wind climate, most notably by Davenport et al. (1984), Melbourne (1984) and Hitchcock et al. (2003). Melbourne (1984) conducted wind tunnel model studies to determine directional factors relating wind speeds at each anemometer location to the wind speed at a elevation equivalent to 50 mPD in the free stream flow and concluded that:

- Measurements taken during the period 1 January 1964 to 11 July 1966 inclusive were directly and adversely affected by the effects of the building on which it was mounted; therefore, records from that period were excluded from that study.

- The anemometer correction factors for mean wind speeds show some sensitivity to the modelled approach flow but they are not strongly dependent on the modelled approach profiles.
- The largest magnitude speed-up effects occur for winds approaching from approximately 67.5°, 180°, 270° and 360°.
- The largest magnitude slow-down effects occur for winds approaching from approximately 112.5°, 225° and 315°.

In the study conducted by Hitchcock et al. (2003), wind tunnel tests were undertaken to correct wind records for position and topographical effects at the four anemometer locations used since 1952, with the exception of the location used during the period 1 January 1964 to 11 July 1966 inclusive. In that study, thermal (hotwire) anemometer measurements were taken at 22.5° intervals for the full 360° azimuth relating wind speeds at anemometer height to wind speeds at a elevation equivalent to 200 mPD in the free stream. The directional characteristics of the former anemometer sites were found to be similar to those discussed by Davenport et al. (1984) and Melbourne (1984), whereas the current anemometer site is much less affected than its predecessors, due mainly to its additional height.

Correction factors were determined and subsequently applied to non-typhoon wind data collected at Waglan Island to determine a probability distribution of directional mean wind speeds for Hong Kong. The corresponding annual wind rose for mean wind speeds at a elevation equivalent to 500 mPD above open water is presented in Figure 3 and indicates that, on an annual basis, prevailing and strong non-typhoon winds approaching Hong Kong occur mainly from the north-east quadrant and, to a lesser extent, the south-west. The summer (i.e. June, July, August) wind rose for mean wind speeds at an elevation equivalent to 500 mPD above open water is presented in Figure 4. In contrast to the corresponding annual wind rose, prevailing and strong non-typhoon winds approaching Hong Kong during summer months occur mainly from the south-east and south-west quadrants.

In Figures 3 and 4, mean wind speeds are segregated into four categories (0 – 3.3 m/s, 3.4 – 7.9 m/s, 8.0 – 13.8 m/s and greater than 13.8 m/s) that are indicated by the thickness of the bars for the 16 cardinal wind directions. The length of the bars indicates the average percentage of occurrence per year. For example, Figure 3 illustrates that, on an annual basis, east winds occur approximately 24% of the time and hourly mean wind speeds exceed 13.8 m/s approximately 6% of the time at an elevation of 500 mPD.

3 WIND TUNNEL STUDY

The wind tunnel test techniques used in this investigation are in accordance with the procedures and recommendations of the Australasian Wind Engineering Society Quality Assurance Manual, AWES QAM-1-2001 (2001) and the American Society of Civil Engineers Manual and Report on Engineering Practice No. 67 for Wind Tunnel Studies of Buildings and Structures (1999). Those requirements cover the satisfactory modelling of the turbulent natural wind, the accuracy of the wind tunnel models, experimental and analysis procedures, and quality assurance.

3.1 Modelling the Natural Wind

Air moving relative to the Earth's surface has frictional forces imparted on it, which effectively cause it to be slowed down. These forces have a decreasing effect on airflow as the height above ground increases, generally resulting in mean wind speed increasing with height to a point where the effects of surface drag become negligible. In wind engineering, a convenient measure of the thickness of the atmospheric boundary layer is commonly referred to as the gradient height which will vary depending on the surrounding surface roughness over which the air will flow. Obstacles to air flow can vary from relatively large expanses of smooth, open water, to vegetation such as forests, built-up environments such as city centres, and large, rugged mountain ranges. The resulting gradient heights typically vary from several hundred metres to in excess of 1000 m.

Winds within the atmospheric boundary layer are also usually highly turbulent or gusty. Turbulence intensity is a measure of the gustiness of wind due to eddies and vortices generated by frictional effects at surface level, the roughness of the terrain over which air is flowing and convective effects due to opposing movements of air masses of different temperature. In typical atmospheric boundary layer flow, turbulence intensity generally decreases with height. Closer to the ground, at pedestrian level for example, the magnitude of the turbulence intensity can be very large due to the effects of wind flowing around buildings and other structures.

In conducting wind tunnel model studies of wind characteristics and wind effects on and around tall buildings and other structures on the surface of the Earth, it is necessary to adequately simulate the relevant characteristics of atmospheric boundary layer flow. WWTF's boundary layer wind tunnel test sections can be used to simulate atmospheric boundary layer flow over various types of terrain, ranging from open terrain, such as open water, to urban or mountainous terrain.

WWTF comprises two long fetch boundary layer wind tunnel test sections as shown in Figure 5. The 28 m long high speed test section has a 3 m wide × 2 m high working section and a maximum free stream wind speed of approximately 30 m/s. The 40 m long low speed test section has a 5 m wide × 4 m high working section and a maximum free-stream wind speed of approximately 10 m/s. Various terrains can be modelled in either test section at length scales ranging from approximately 1:5000 to 1:50.

The characteristics of the wind flow in the low speed test section can be modified through the use of devices such as spires, grids, and fences to model various atmospheric boundary layer flows. For the current study, WWTF's low speed test section was calibrated by using various roughness elements to simulate the wind speed and turbulence intensity characteristics corresponding to wind flow above open water. The mean wind speed profile of the wind flow approaching the Study Area was simulated in accordance with the power law expression, defined in Equation (1), specified in Planning Department's Feasibility Study for Establishment of Air Ventilation Assessment System – Final Report (2005).

$$\frac{V_{z,open}}{V_{ref,open}} = \left(\frac{z}{z_{ref}} \right)^{\alpha} \qquad (1)$$

where

$V_{z,open}$ = mean wind speed at a height z above open water terrain (m/s);

$V_{ref,open}$ = mean wind speed at a height z_{ref} above open water terrain (m/s);

z = height above zero plane displacement (m);

z_{ref} = a suitable reference height above open water terrain (m);

α = a power law exponent, which is a constant commensurate with the terrain roughness, taken as 0.15 for this study.

The turbulence intensity profile of the approaching wind flow was simulated in accordance with Terrain category 2 stipulated in Australian/New Zealand Standard AS/NZS 1170.2:2002, i.e. corresponding to non-typhoon wind flow above rough open water surfaces.

The simulated mean wind speed and turbulence intensity profiles were generally within ±10% of the target mean speed and turbulence intensity profiles and they are presented in Figure 6. The spectrum of longitudinal turbulence of the approaching wind flow measured at an elevation equivalent to 500 mPD in prototype scale is presented in Figure 7.

3.2 Physical Model of the Study Area

WWTF has a 1:2000 scale topographical model of the New Territories, Kowloon and Hong Kong Island fabricated at 20 m contour intervals from information acquired from the Survey and Mapping Office of The Government of the Hong Kong Special Administrative Region (HKSAR) Lands Department. The relevant sections of the topographical model were updated to include all known current buildings and the major topographical features in the urban landscapes of Hong Kong Island, Kowloon Peninsula and the New Territories. For all wind directions tested, the wind tunnel model included surrounding areas within a distance of up to approximately 10 km from the Study Area.

The topographical model was updated to include greater detail within a zone from 500 m up to approximately 1000 m from the Study Area. In accordance with information supplied by the Department of Architecture of The Chinese University of Hong Kong during the period between 13 January 2009 to 29 June 2009, all specified committed developments and all known existing buildings and structures at the time of testing were included in the model to represent their effects on wind flow approaching the Study Area. Beyond the 1000 m radius, the topographical model included roughness representative of the surrounding areas. Several representative views of the 1:2000 scale topographical model used in the current study is shown in Figures 8.

3.3 Experimental and Analysis Procedures

The terrain surrounding the Study Area comprises complex mixtures of built-up environment, and mountainous areas on the Kowloon Peninsula. Winds approaching the modelled region were scaled to simulate non-typhoon winds flowing over open water and the topographical model was used to determine the modifying effects of the surrounding complex terrain on the wind speed and turbulence intensity above the Study Area.

Wind tunnel measurements were taken using a miniature dynamic pressure probe, a Cobra probe manufactured by Turbulent Flow Instrumentation Pty Ltd, at 22.5° intervals for the full 360° azimuth (i.e. 16 wind directions), where a wind direction -of 0° or 360° corresponds to an incident wind approaching the Study Area directly from the north, 90° corresponds to an incident wind approaching the Study Area directly from the east, etc. For each wind direction tested, mean wind speeds and turbulence intensities were measured at elevations equivalent to 25, 50, 75, 100, 150, 200, 300, 400 and 500 mPD in prototype scale, above the centre of the Study Area.

While measurements were taken at the Study Area, all buildings within a diameter of 1000 m of the centre of the Study Area were removed from the wind tunnel model for all measured wind directions. All buildings within the diameter of 1000 m will be included in the proximity model for the 1:400 scale detailed benchmarking study to directly account for their effects on the wind flow within the Study Area.

4 EXPERIMENTAL RESULTS AND DISCUSSION

For each wind direction tested, results of the 1:2000 scale topography study are presented in graphical format in Figures 9 to 24 inclusive and in tabular format in Appendix A. In Figures 9a to 24a, the normalised wind characteristics include the measured mean resultant wind speed profiles and turbulence intensity profiles. Mean wind speed profiles were determined by normalising the local mean wind speeds with respect to the mean wind speed of the approaching wind flow measured at an elevation equivalent to 500 mPD, as defined in Equation (2). Vertical profiles of turbulence intensity, defined in Equation (3), are also presented in Figures 9a to 24a. Yaw and pitch angles, i.e. the lateral and vertical deviations, respectively, of the local mean wind direction relative to the approaching mean wind direction, are presented in Figures 9b to 24b inclusive. The sign conventions used to define yaw angles and pitch angles are provided in Appendix B.

$$\text{Normalised mean wind speed} = \frac{V_{z,site,i}}{V_{500,open,i}} \qquad (2)$$

$$\text{turbulence intensity} = \frac{\sigma_{z,site,i}}{V_{z,site,i}} \qquad (3)$$

In Equations (2) and (3), $V_{z,site,i}$ is the resultant mean wind speed above the site centre at an elevation z = 25, 50, 75, 100, 150, 200, 300, 400 or 500 mPD in prototype scale) for an approaching wind direction i, where i equals to 22.5°, 45°, 67.5°, 90°, 112.5°, 135°, 157.5°, 180°, 202.5°, 225°, 247.5°, 270°, 292.5°, 315°, 337.5° or 360°; $V_{500,open,i}$ is the resultant mean wind speed of the approaching wind at a elevation equivalent to 500 mPD in prototype scale for an approaching wind direction, i; and $\sigma_{z,site,i}$ is the standard deviation of the fluctuating resultant wind speed above the site for an approaching wind direction i. The profiles of resultant mean wind speed and turbulence intensity will be used as input boundary conditions for the detailed benchmarking study for the Study Area.

The topography study measurements were also used to determine directional factors for the 16 measured wind directions, relating the mean wind speeds at elevations equivalent to 50, 100, 200 and 500 mPD above the Study Area to the mean wind speed of the approach flow at a reference height of 500 mPD. Those directional factors were then applied to WWTF's Hong Kong non-typhoon wind climate model, derived from HKO's Waglan Island wind data as discussed in Section 2 of this report, to determine site-specific wind roses pertaining to annual and summer hourly mean wind speeds at elevations of 50, 100, 200 and 500 mPD above the Study Area. The annual wind roses are presented in Figures 25 to 28 inclusive for elevations of 50 , 100, 200 and 500 mPD above the Sha Tin Study Area, respectively. The summer wind roses are presented in Figures 29 to 32 inclusive for elevations of 50, 100, 200 and 500 mPD above the Sha Tin Study Area, respectively. Wind rose data are presented in tabular format in Appendix A.

4.1 Wind characteristics of the Sha Tin Study Area

The nominated Study Area in Sha Tin is situated to the south-east of the Shing Mun river channel, and is shown in Figures 1 and 2. The Shing Mun river channel is located within the Sha Tin district, which comprises of a mixture of high and low rise urban and residential buildings.

Sha Tin District is also surrounded by many high mountain peaks and hills. These hills include Kau To Shan, approximately 2 km to the north of the Study Area with an elevation of 399 mPD. Approximately 2.3 km west of the Study Area is Needle Hill with an elevation of 532 mPD. Additionally there are two hills located about 1.5 km from the Study Area, Nui Po Shan to the east at 399 mPD and Ngau Au Shan to the south-east with an elevation of 370 mPD. In the south direction, approximately 6 km from the Study Area, there are several large peaks located in Lion Rock Country Park. These peaks include Lion Rock with an elevation of 495 mPD and Kowloon Peak at 602 mPD. In the south-east direction, approximately 4 km from the Study Area, are Kwun Yam Shan and Tate's Cairn with elevations of 546 mPD and 583 mPD respectively. To the east, approximately 6 km from the Study Area, is Ma On Shan and Pyramid Hill with elevations of 702 mPD, and 536 mPD respectively. Approximately 6 km to the south-west of the Study Area is Beacon Hill and Golden Hill with elevations of 457 mPD and 369 mPD respectively. Tai Mo Shan is located approximately 6 km to the north-west of the Study Area. .

The open stretch of water at Sha Tin Hoi is located to the north-east of the Study Area and the large urban area of Kowloon lies to the south, beyond Lion Rock Country Park.

Significant overall reductions to the magnitude of the mean wind speed profiles were measured for all wind directions at all measured elevations due to the effects of the mountains for those wind directions. The most significant reductions were measured for wind directions of 180° 202.5°, 225° and 247.5°, and the magnitudes of turbulence intensity were increased to approximately 27% to 30%. This is attributed to combination of buildings and the large peaks of Lion Rock, Kowloon Peak, Beacon Hill and Golden Hill to the south and south-west of the Study Area.. Furthermore, the presence of the large urban areas of Kowloon and Kowloon Bay further south of the Study Area are also to affect the magnitudes of mean velocity and turbulence intensity from those wind directions.

Similar effects were also observed for wind directions of 0º, 22.5º, 45º, 90º, 112.5º, 135º, 157º and 225 º due to the effects of the buildings and mountains. For wind directions of 270°, 292.5° and 315°, mean wind speeds measured at elevations below 150 mPD were also reduced significantly, with correspondingly higher magnitudes of turbulence intensity. These effects were attributed to the effects of Needle Hill and Tai Mo Shan to the west and north-west of the Study Area.

Winds approaching the Study Area from a direction of 67.5° are the least affected, particularly at higher elevations, due to the fetch of open sea at Sha Tin Hoi. The corresponding turbulence intensity for this wind direction was also smaller in comparison to the other wind directions.

Significant yaw angles, i.e. exceeding ±11.25°, were measured at elevations below 25 mPD for wind directions of 22.5°and 45° due to the combination of the buildings and Kau To Shan to the north of the Study Area. For wind directions of 180° and 202.5°, large yaw angles were also measured for elevations below 100 mPD. This is attributed to the presence of high mountains and buildings located to the south and south-west of the Study Area.

A comparison of the annual and summer wind roses at 500 mPD presented in Figures 3 and 4 to those for the Sha Tin Study Area in Figures 28 and 32 highlights the reductions in the overall magnitudes of wind speed. At elevations of 150 mPD and below, the mean wind speed changes due to the combination of the effects of the buildings and mountains.

5 CONCLUSIONS

A study of wind availability and characteristics was conducted by the CLP Power Wind/Wave Tunnel Facility at The Hong Kong University of Science and Technology for the nominated Study Area in Sha Tin as part of the "Urban Climate Map and Standards for Wind Environment – Feasibility Study". The study was conducted at the request of the Department of Architecture, The Chinese University of Hong Kong, on behalf of Planning Department of The Government of Hong Kong Special Administrative Region.

A 1:2000 scale topography study was undertaken to determine the effects of local topography and the surrounding urban environment on mean wind speeds and turbulence intensities above the Study Area. The topography study results were subsequently combined with a statistical model of the Hong Kong wind climate, based on measurements of non-typhoon winds taken by Hong Kong Observatory at Waglan Island, to determine directional wind characteristics and availability for the Sha Tin Study Area.

In general, the annual prevailing wind characteristics corresponding to non-typhoon winds at an elevation of 500 mPD above the Sha Tin Study Area were similar to the overall characteristics of non-typhoon winds approaching the Hong Kong region, although the magnitudes of the directional wind speeds were reduced.

Significant reductions in the measured magnitudes of wind speed were mainly caused by the mountains surrounding the Study Area. These mountains significantly affected the directional characteristics for all wind directions except for the wind direction

67.5° . The winds approaching the Study Area from 67.5° were the least affected due to the relatively open fetch of sea at Sha Tin Hoi.

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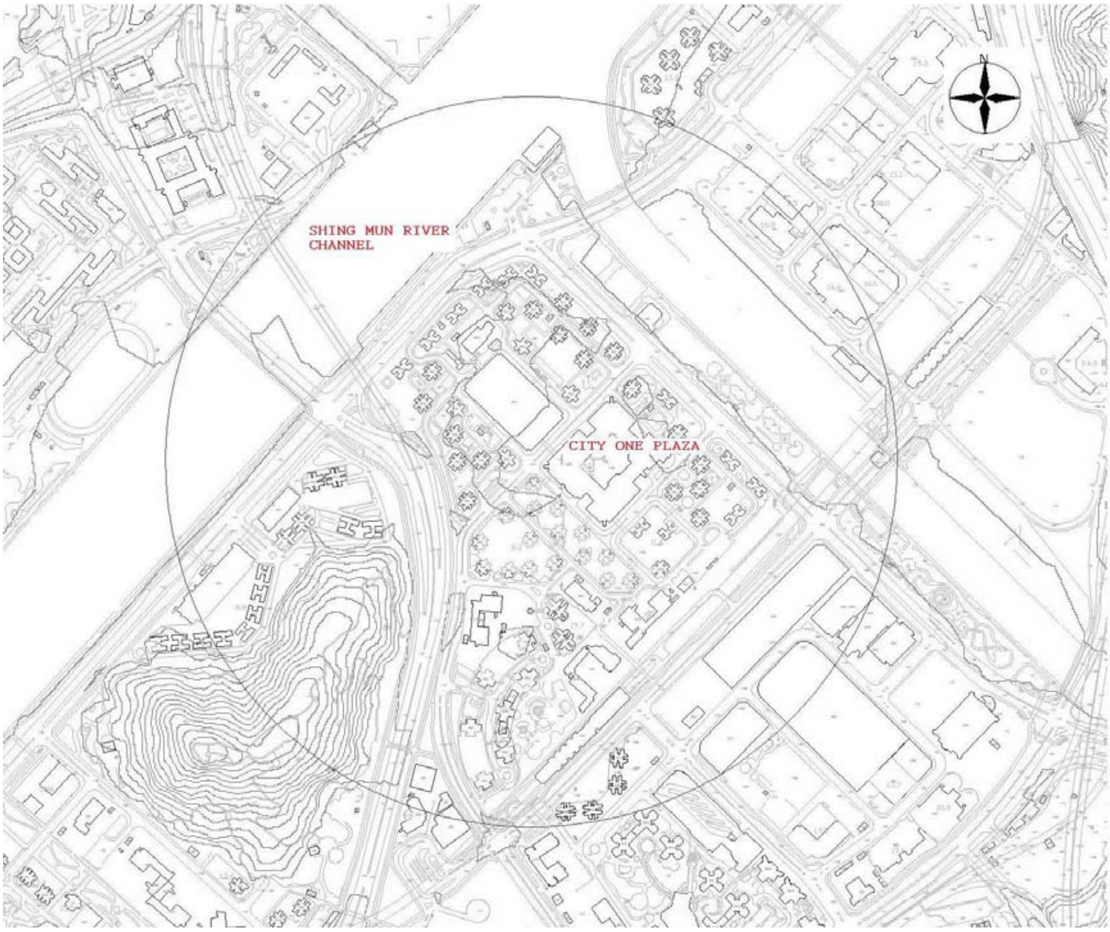

Figure 1: Sha Tin Study Area

Figure 2: Location of the Sha Tin Study Area

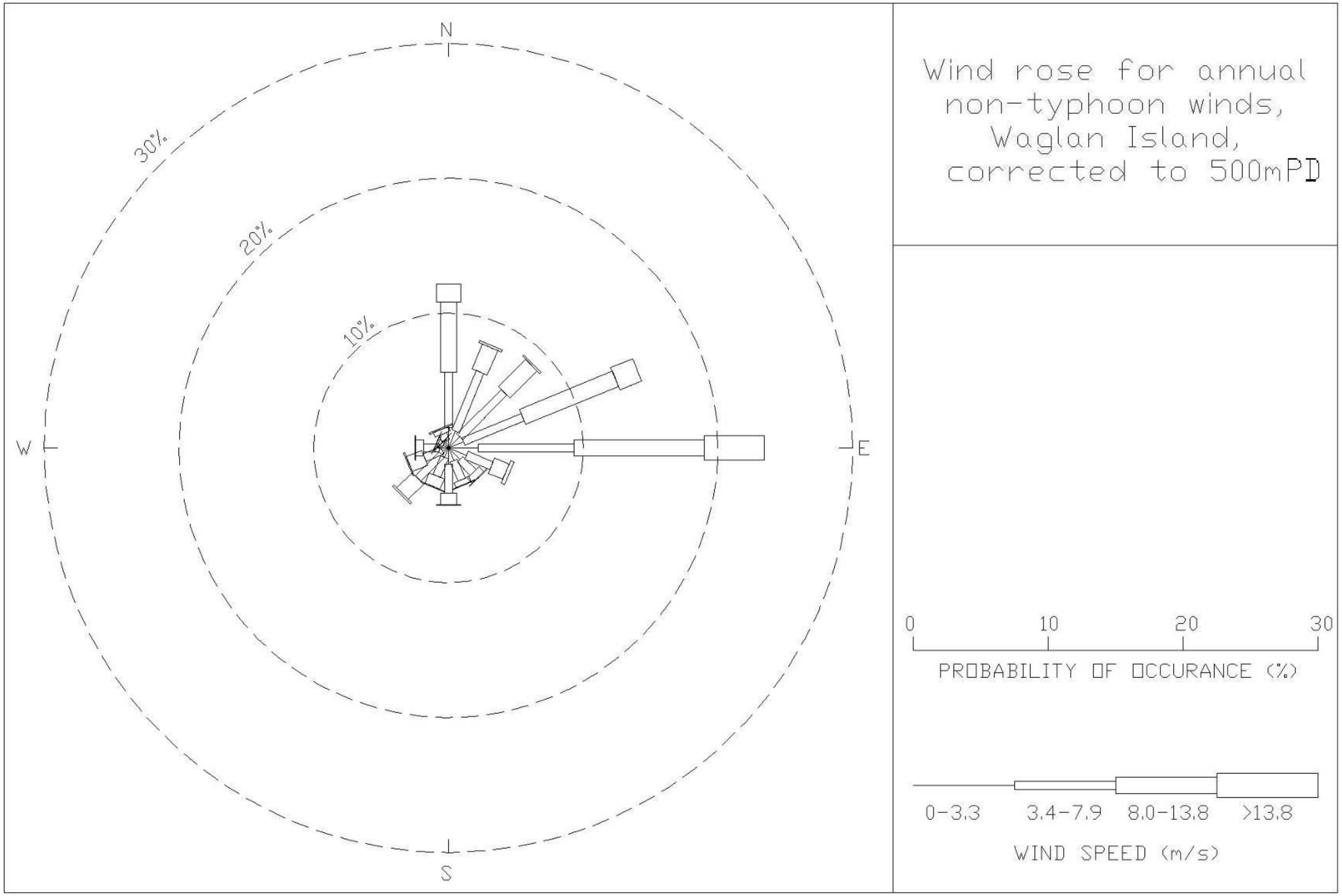

Figure 3: Wind rose for annual non-typhoon winds, Waglan Island, corrected to 500 mPD above open water, 1953-2006

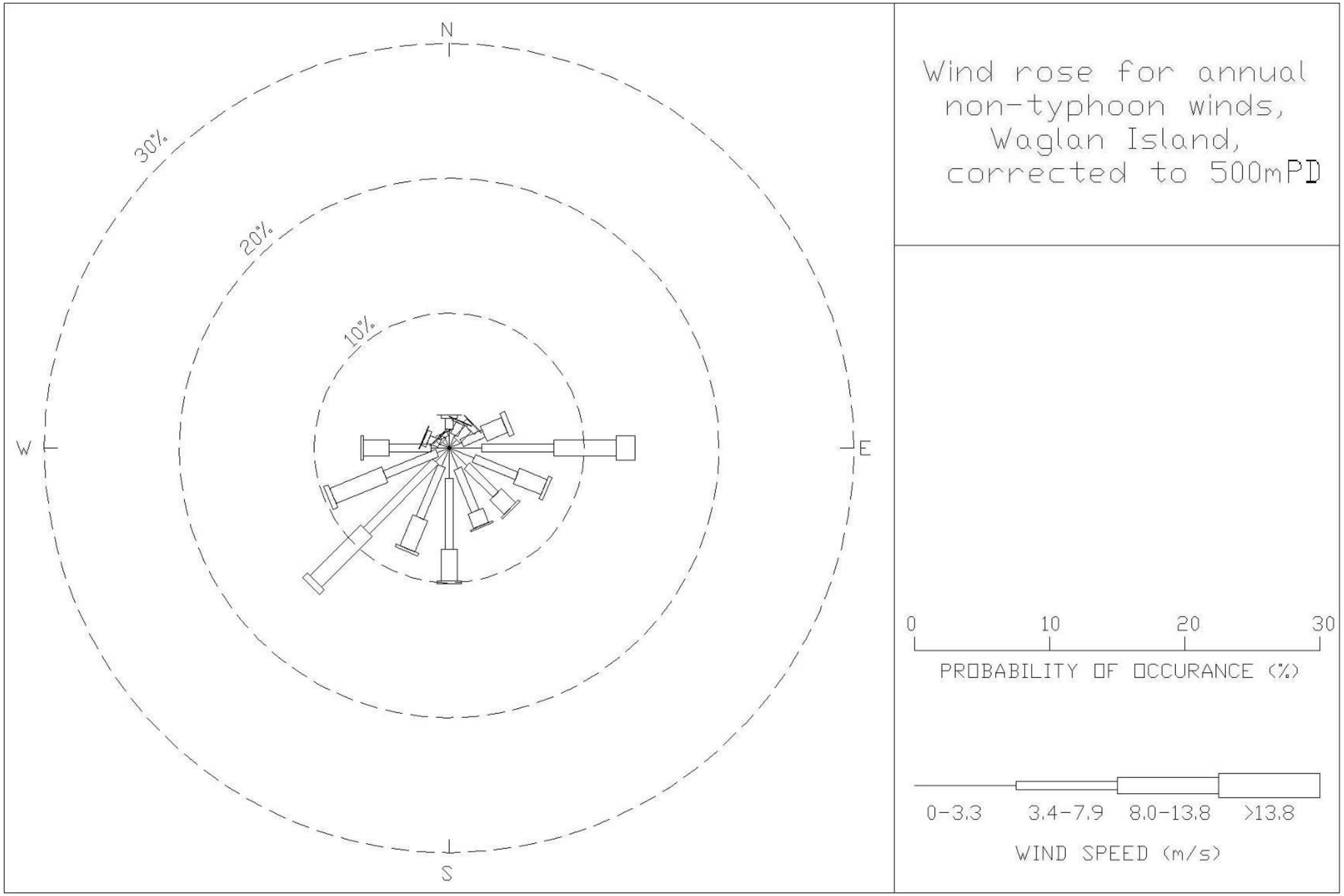

Figure 4: Wind rose for summer non-typhoon winds, Waglan Island, corrected to 500 mPD above open water, 1953-2006

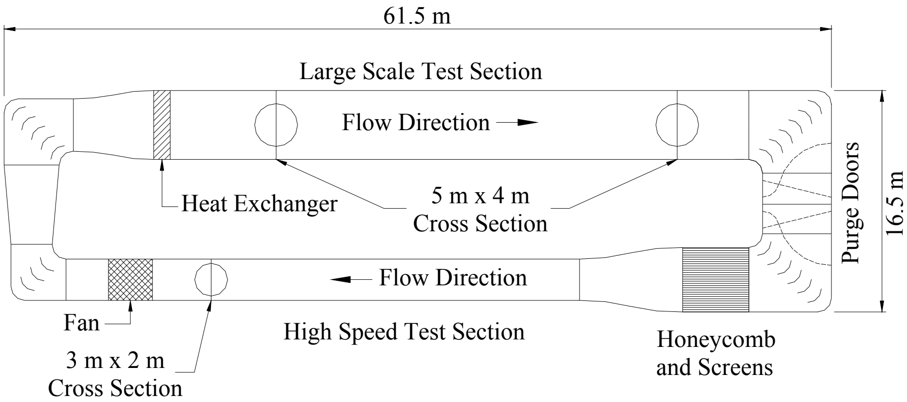

Figure 5: Wind tunnel test sections at the CLP Power Wind/Wave Tunnel Facility

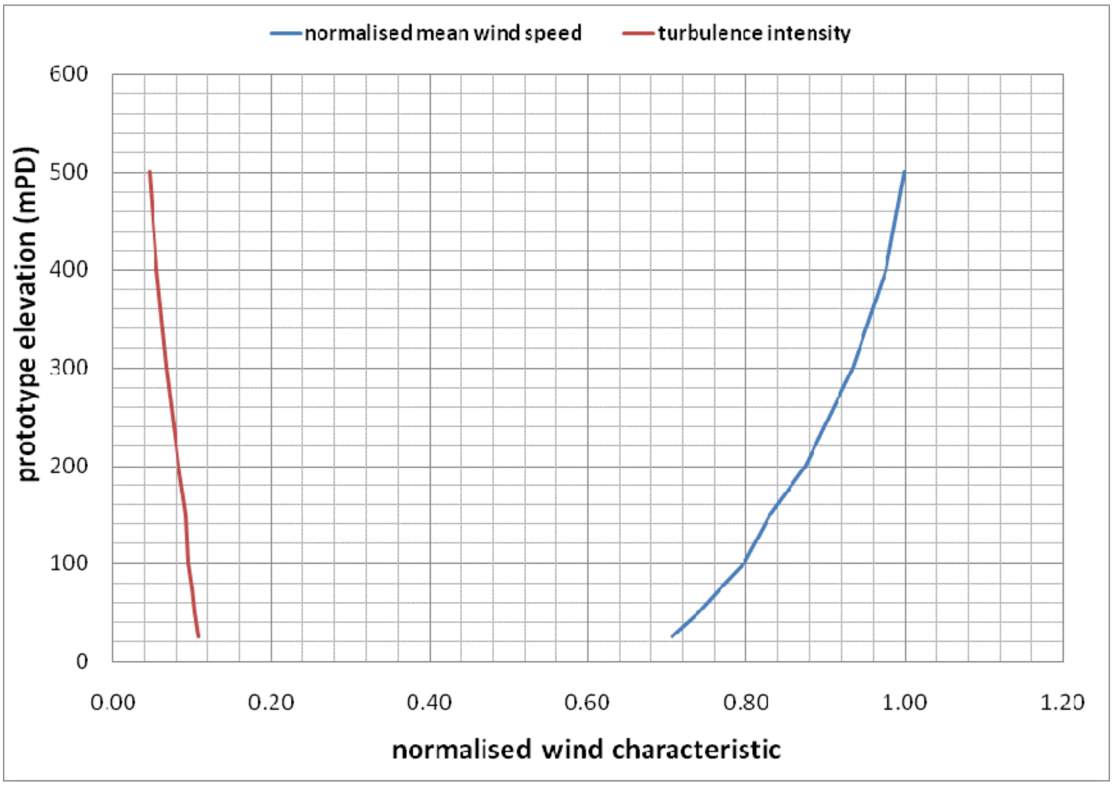

Figure 6: Simulated mean wind speed and turbulence intensity profiles of approach wind

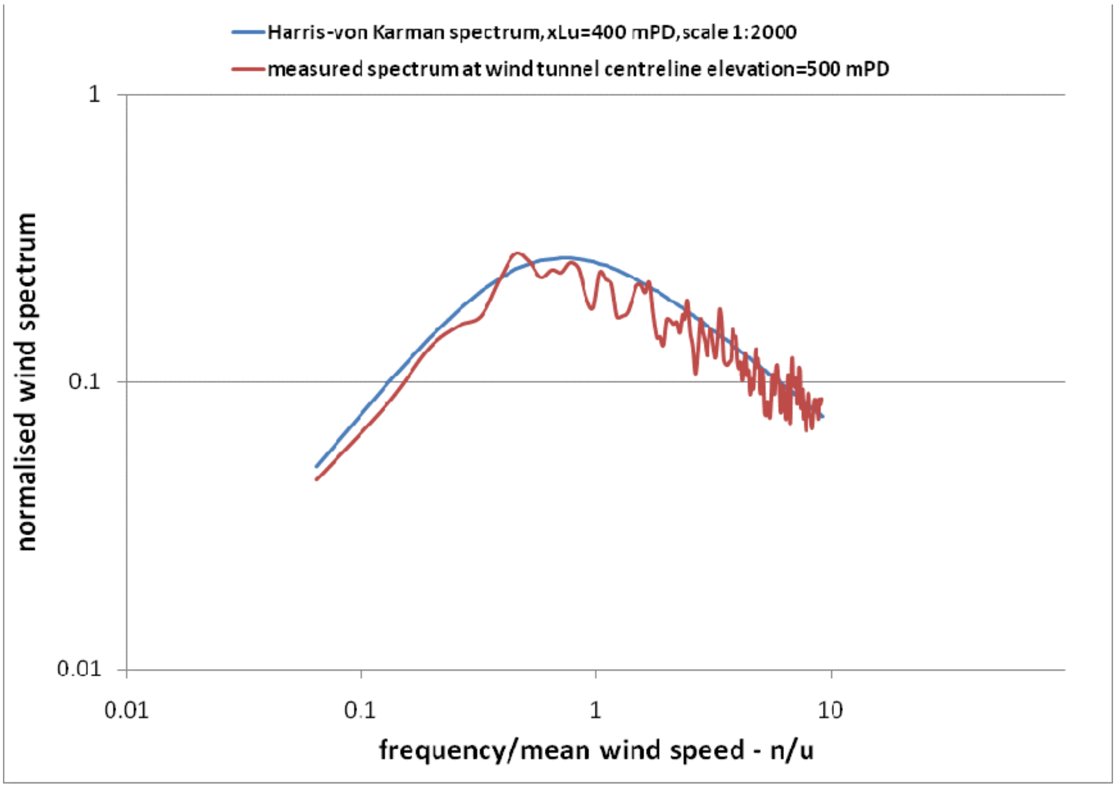

Figure 7: Longitudinal turbulence spectrum of approach wind

(a) North wind direction, 360°

(b) East wind direction, 90°

(c) South wind direction, 180°

(d) West wind direction, 270°

(e) Figure 8: 1:2000 scale topographical model of Sha Tin in the low speed test section of the CLP Power Wind/Wave Tunnel Facility

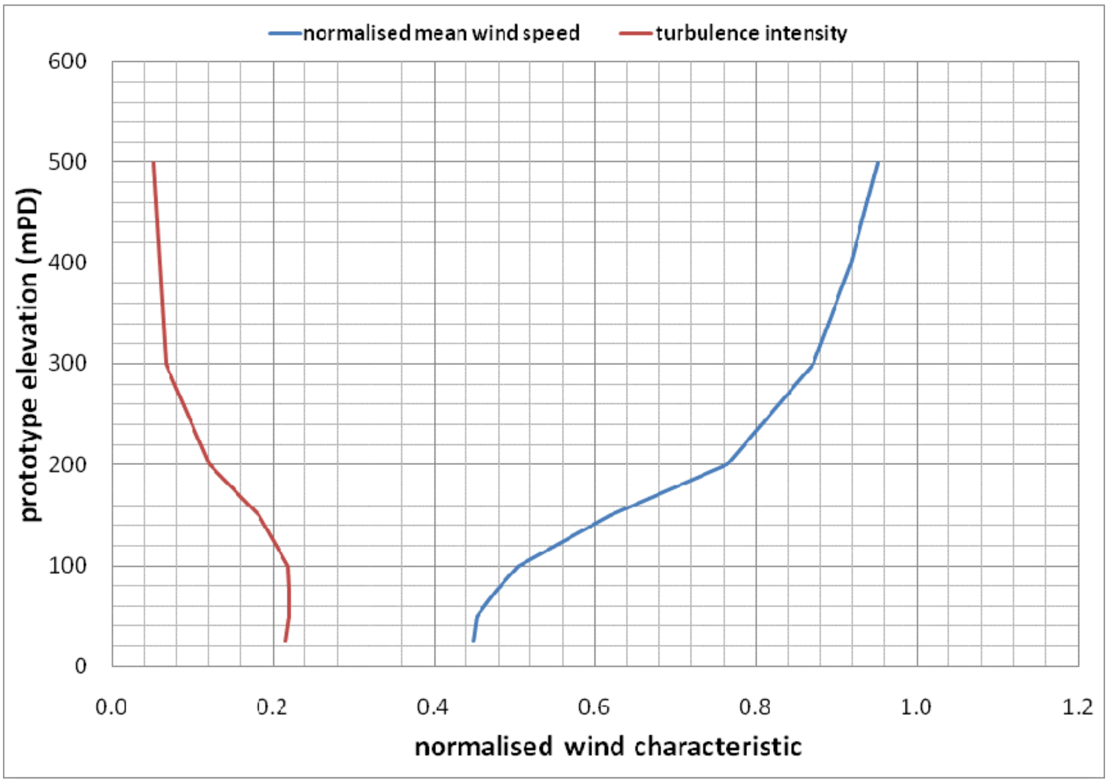

Figure 9a: Wind characteristics for Sha Tin,22.5°

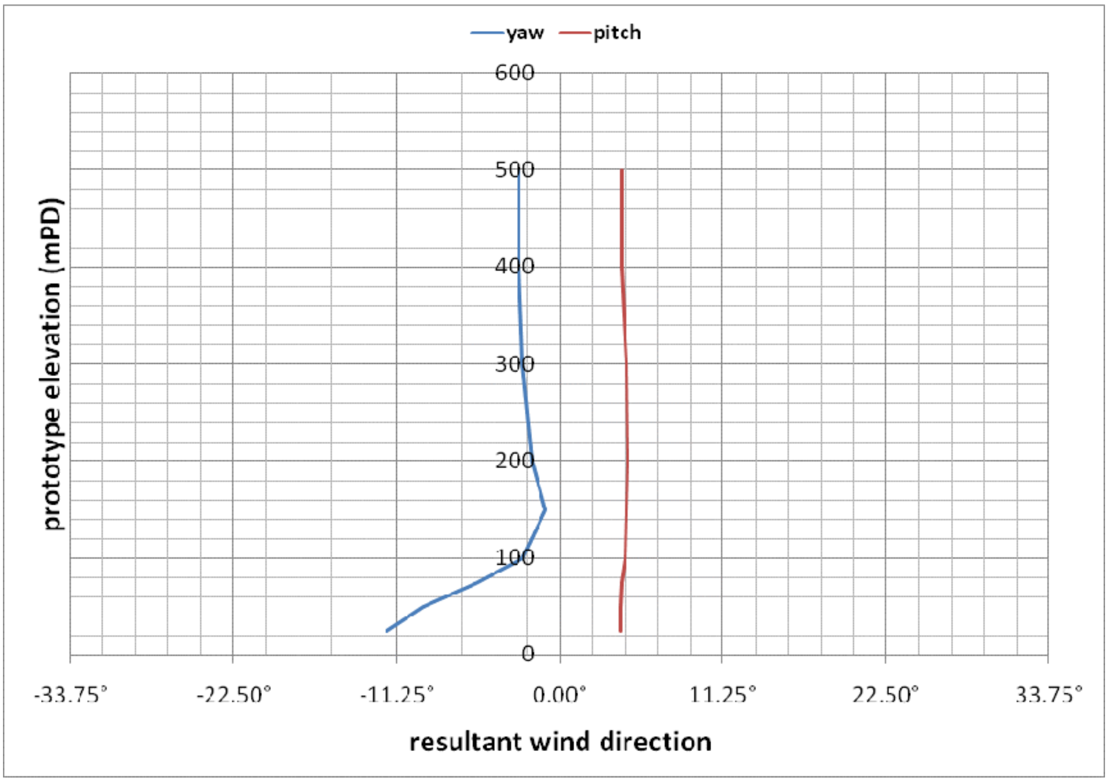

Figure 9b: Mean wind directions for Sha Tin,22.5°

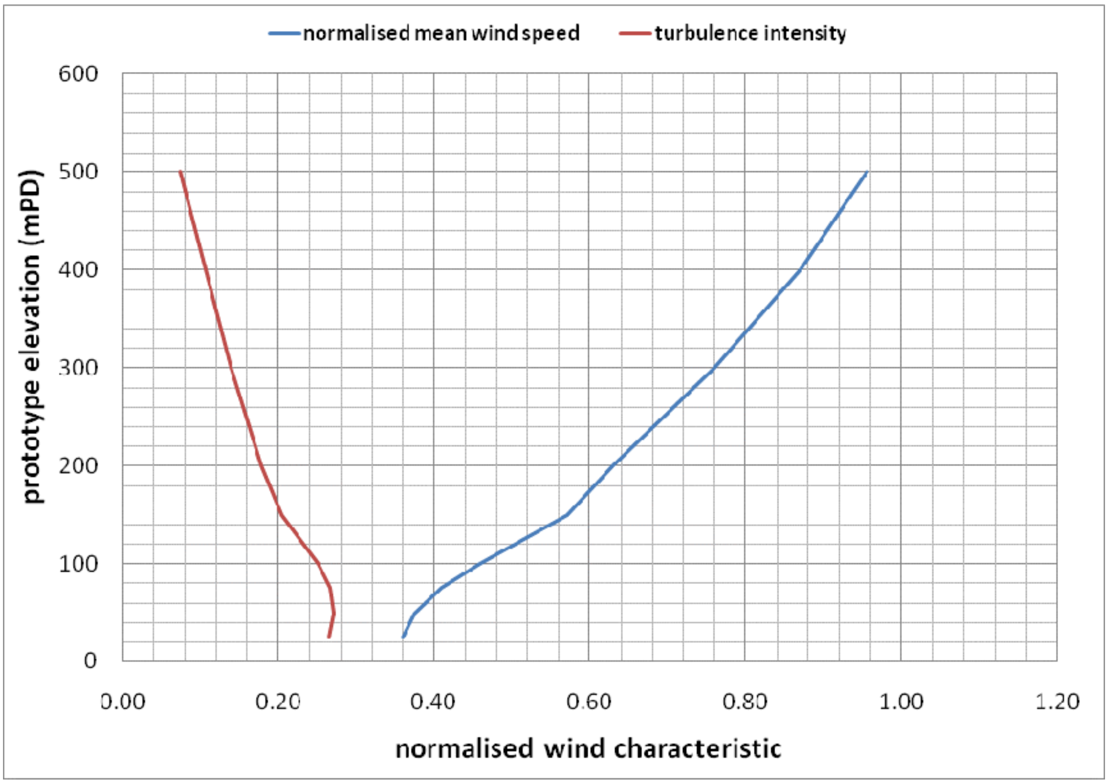

Figure 10a: Wind characteristics for Sha Tin,45°

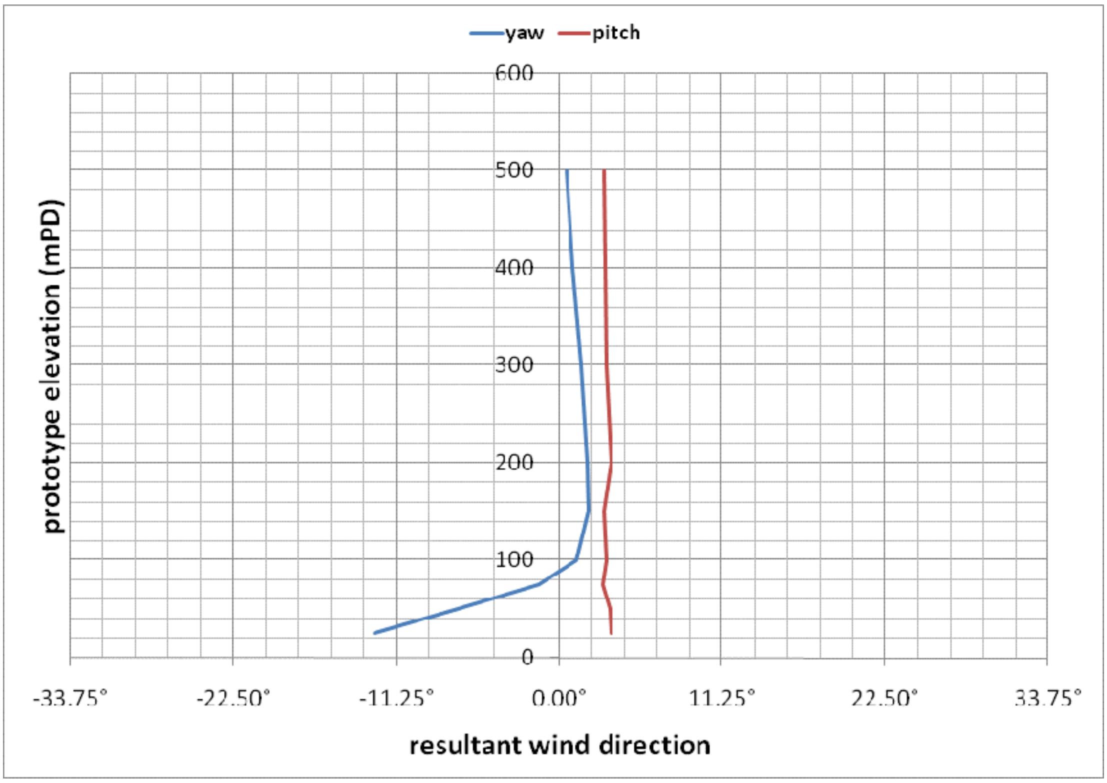

Figure 10b: Mean wind directions for Sha Tin,45°

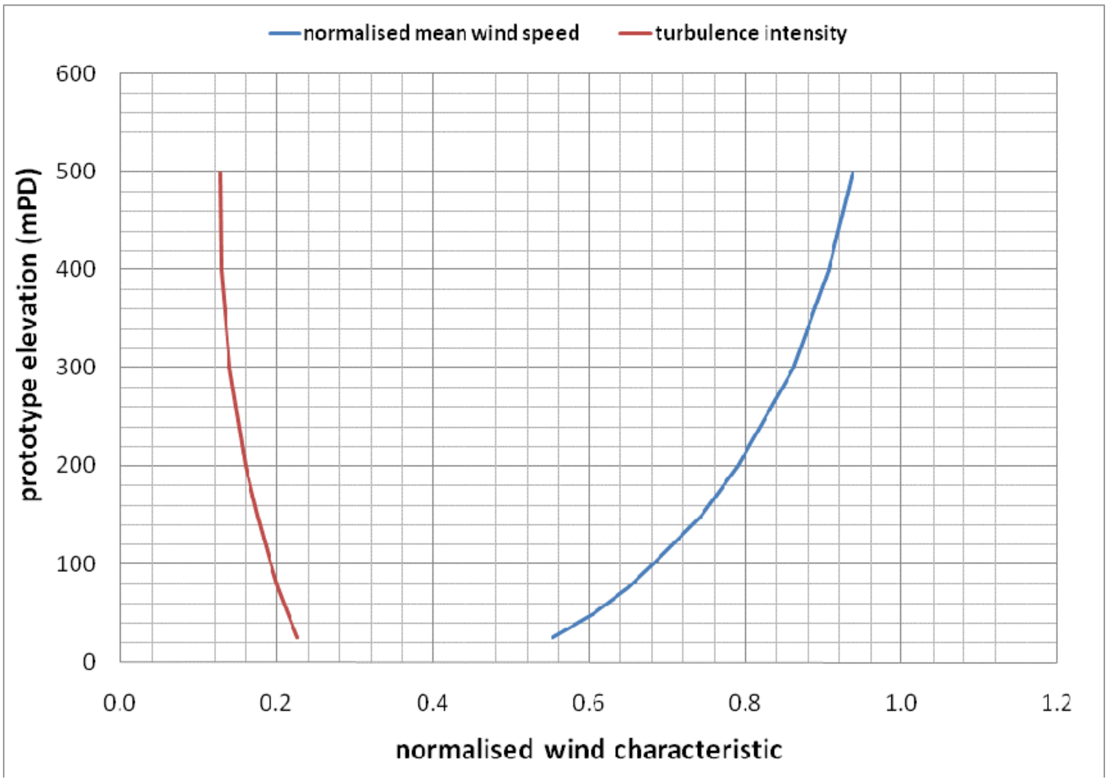

Figure 11a: Wind characteristics for Sha Tin,67.5°

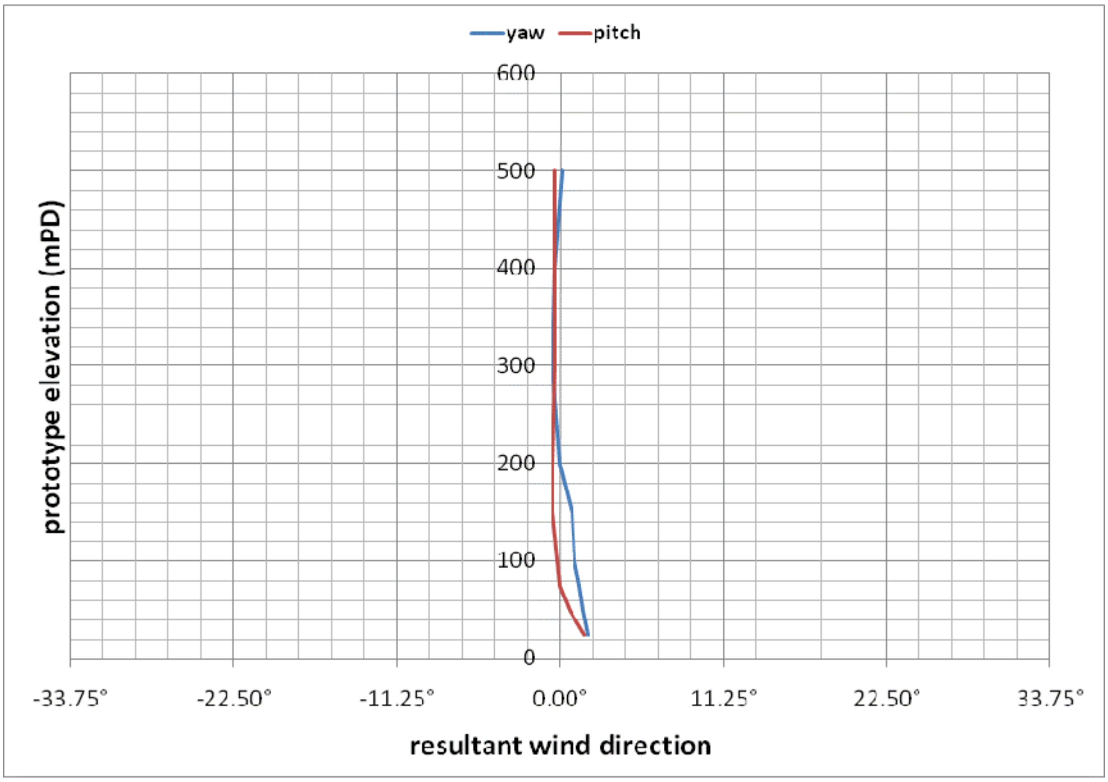

Figure 11b: Mean wind directions for Sha Tin,67.5°

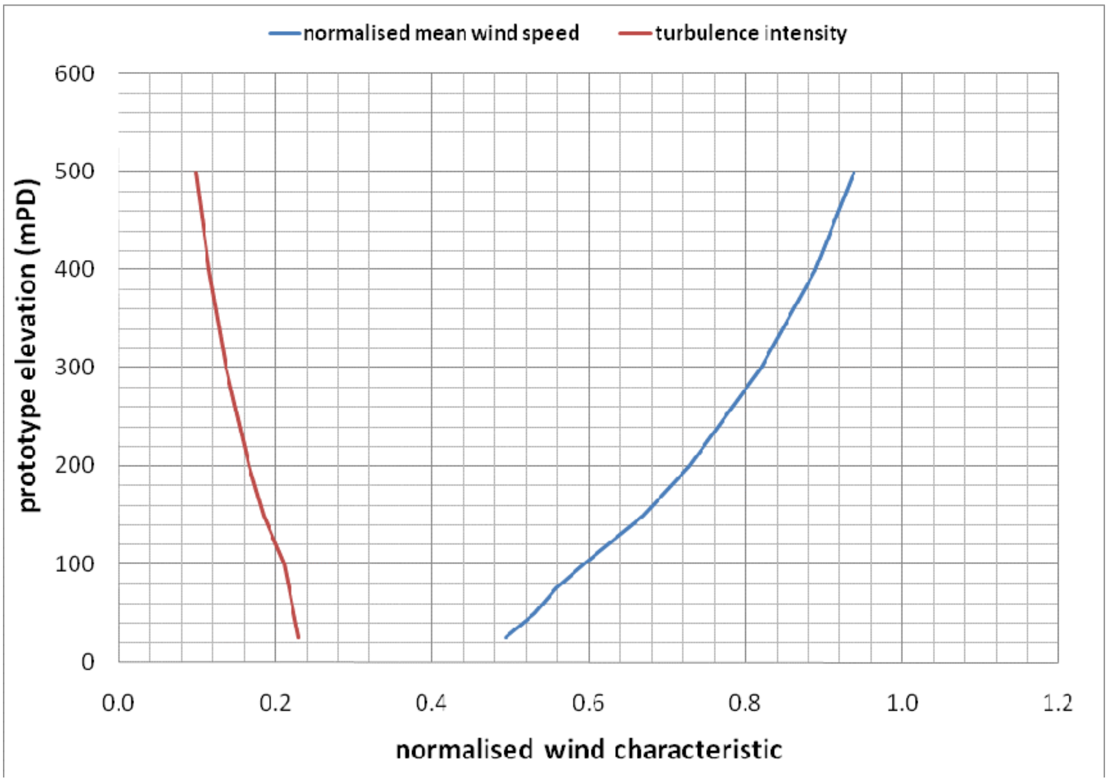

Figure 12a: Wind characteristics for Sha Tin,90°

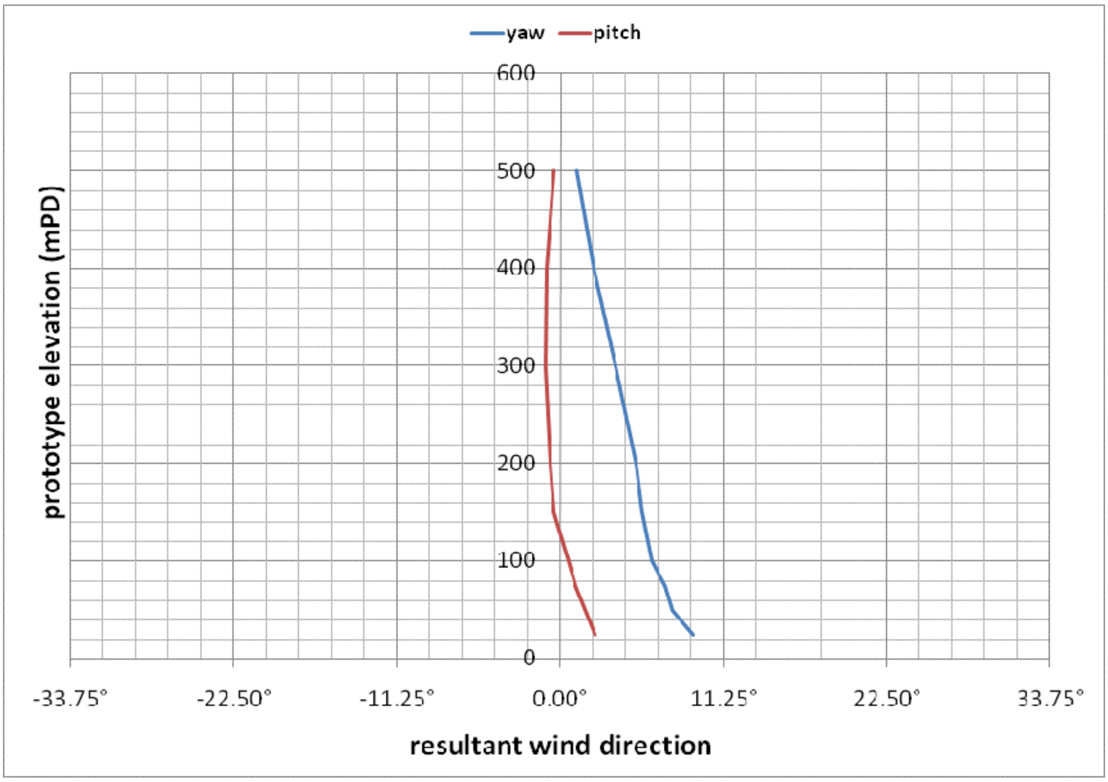

Figure 12b: Mean wind directions for Sha Tin,90°

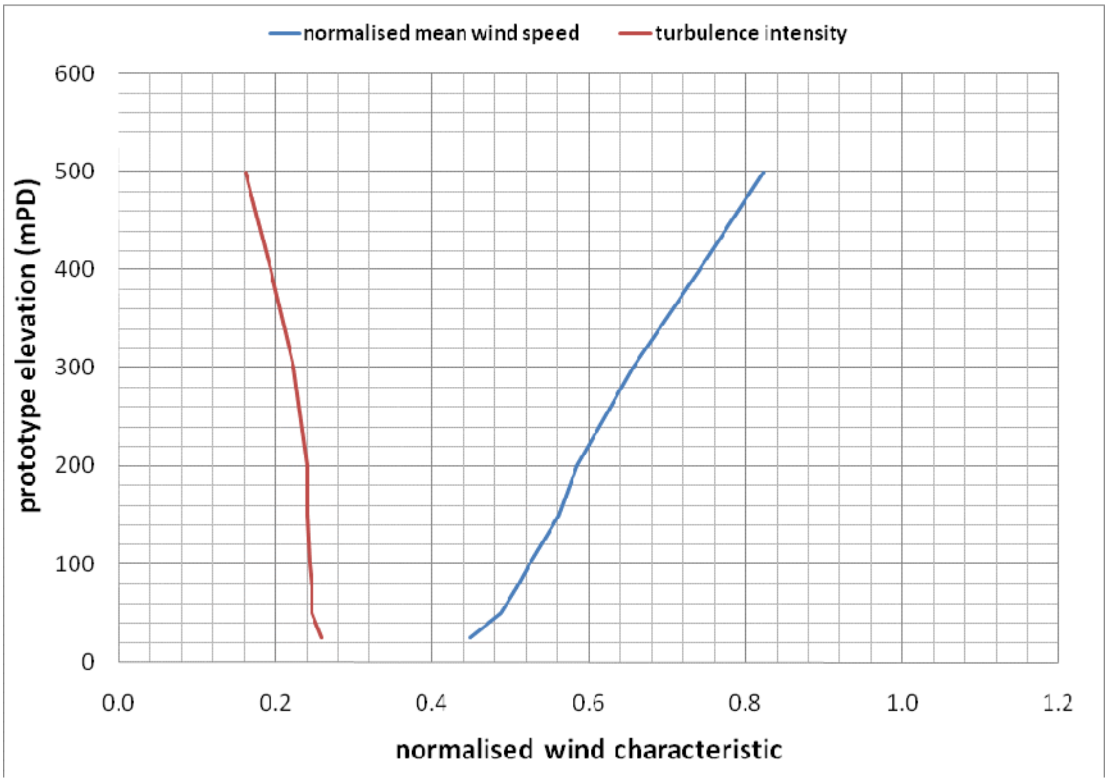

Figure 13a: Wind characteristics for Sha Tin,112.5°

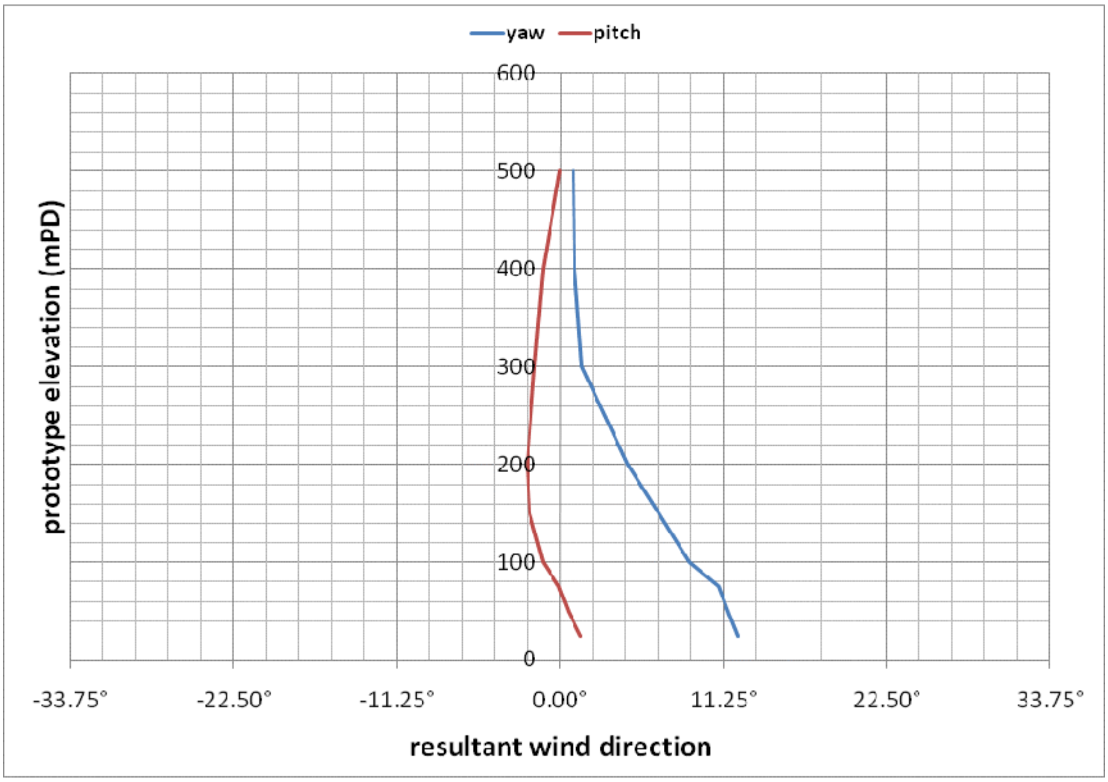

Figure 13b: Mean wind directions for Sha Tin,112.5°

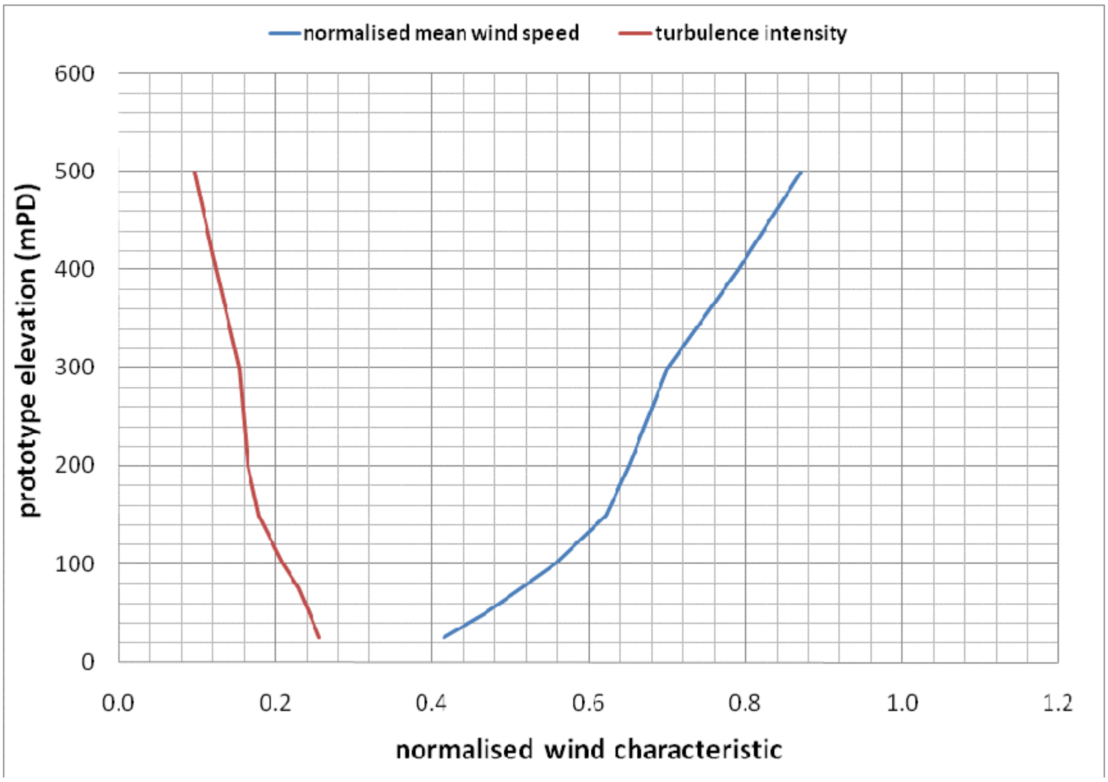

Figure 14a: Wind characteristics for Sha Tin,135°

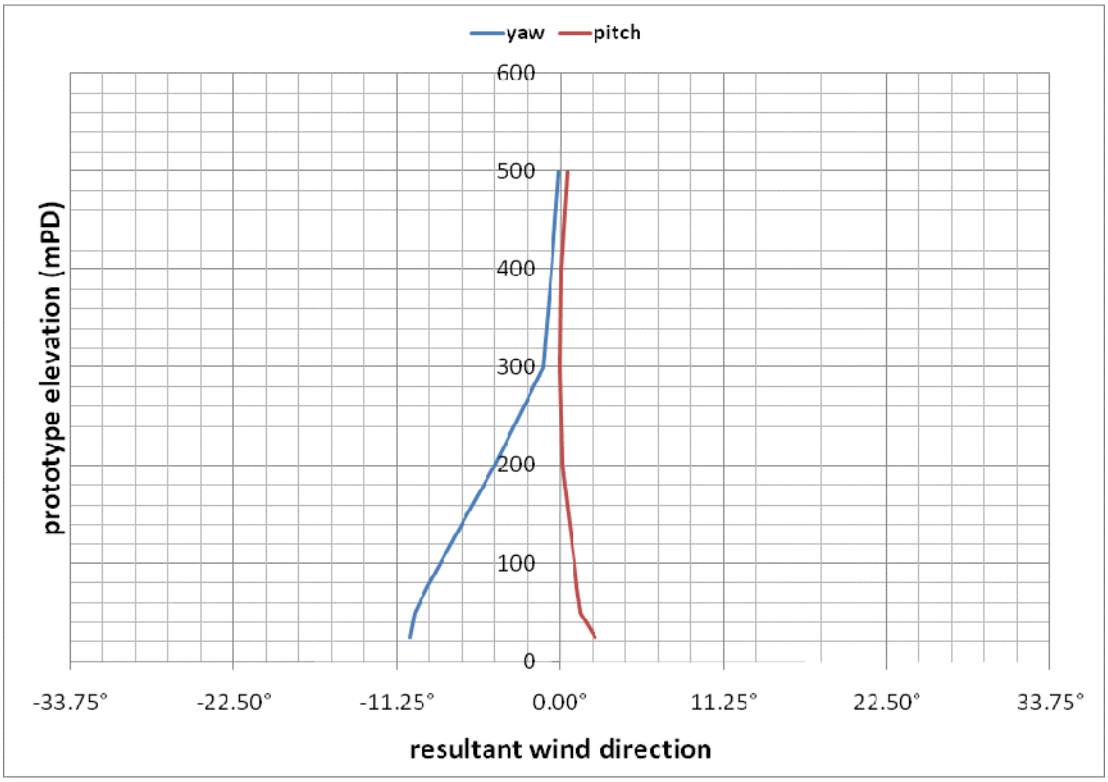

Figure 14b: Mean wind directions for Sha Tin,135°

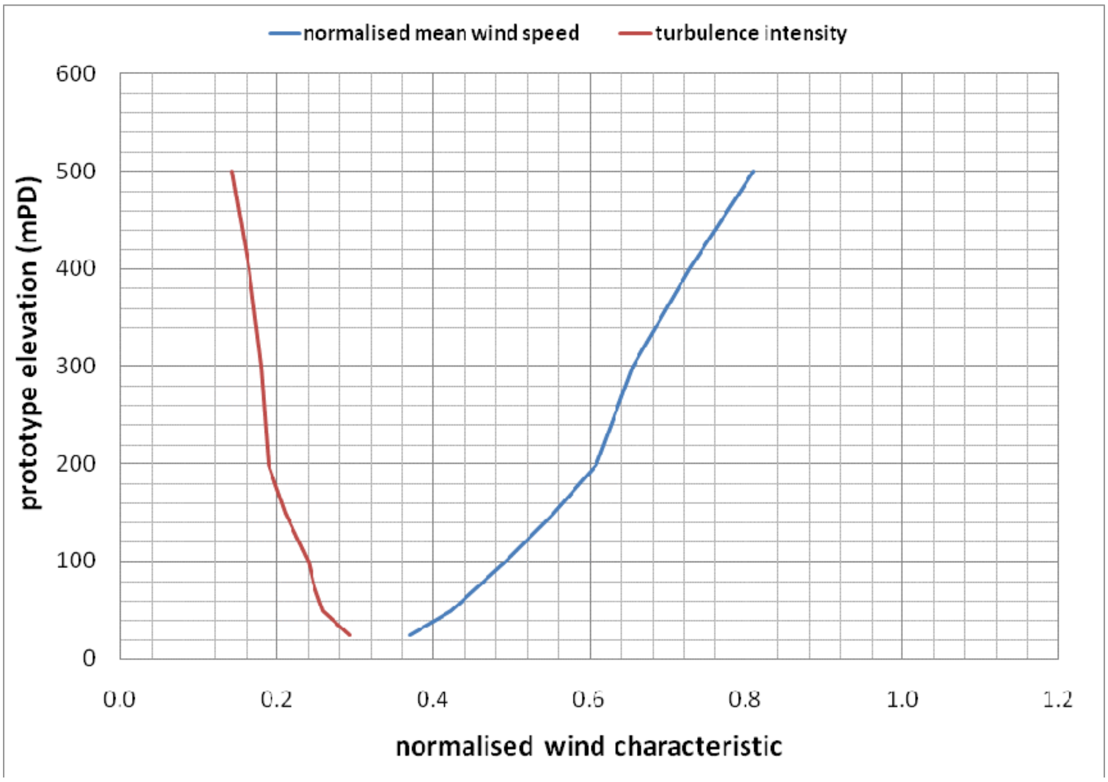

Figure 15a: Wind characteristics for Sha Tin,157.5°

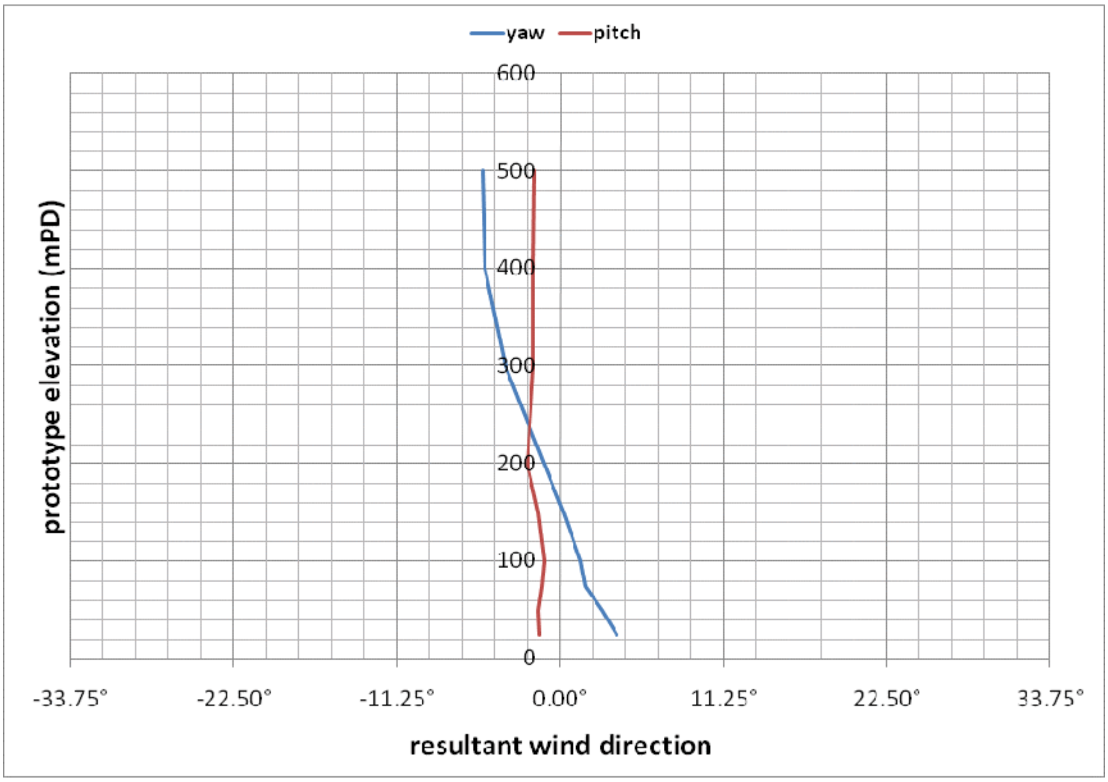

Figure 15b: Mean wind directions for Sha Tin,157.5°

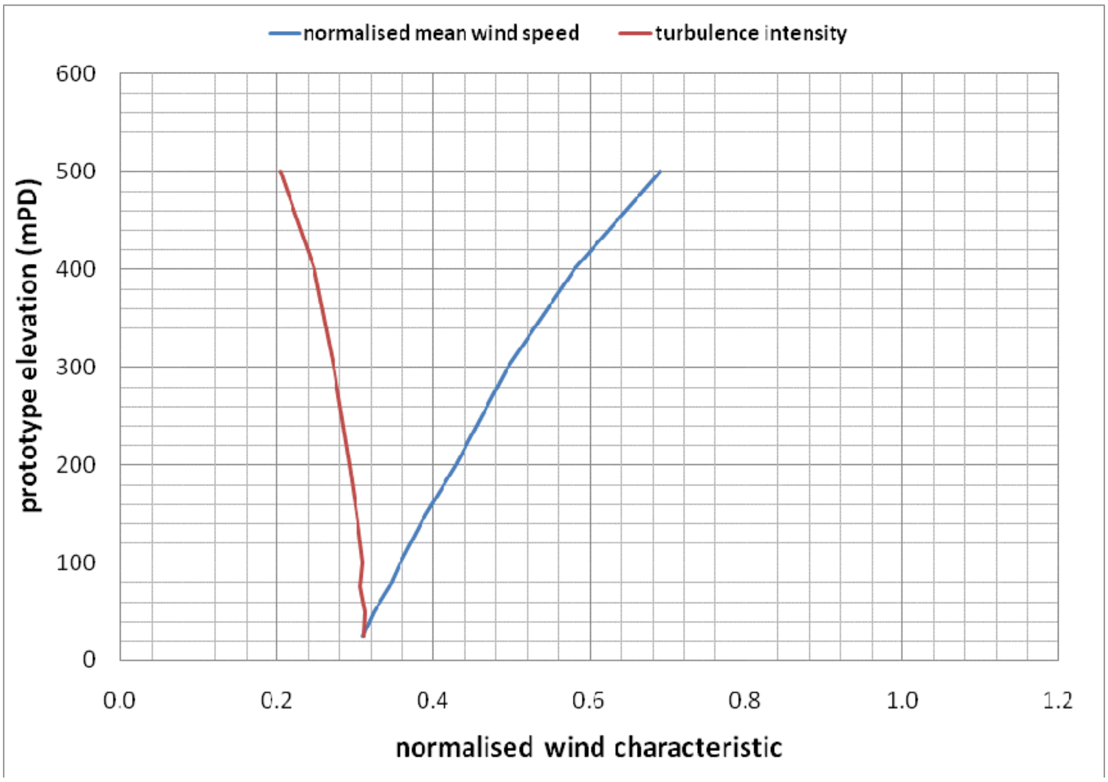

Figure 16a: Wind characteristics for Sha Tin,180°

Figure 16b: Mean wind directions for Sha Tin,180°

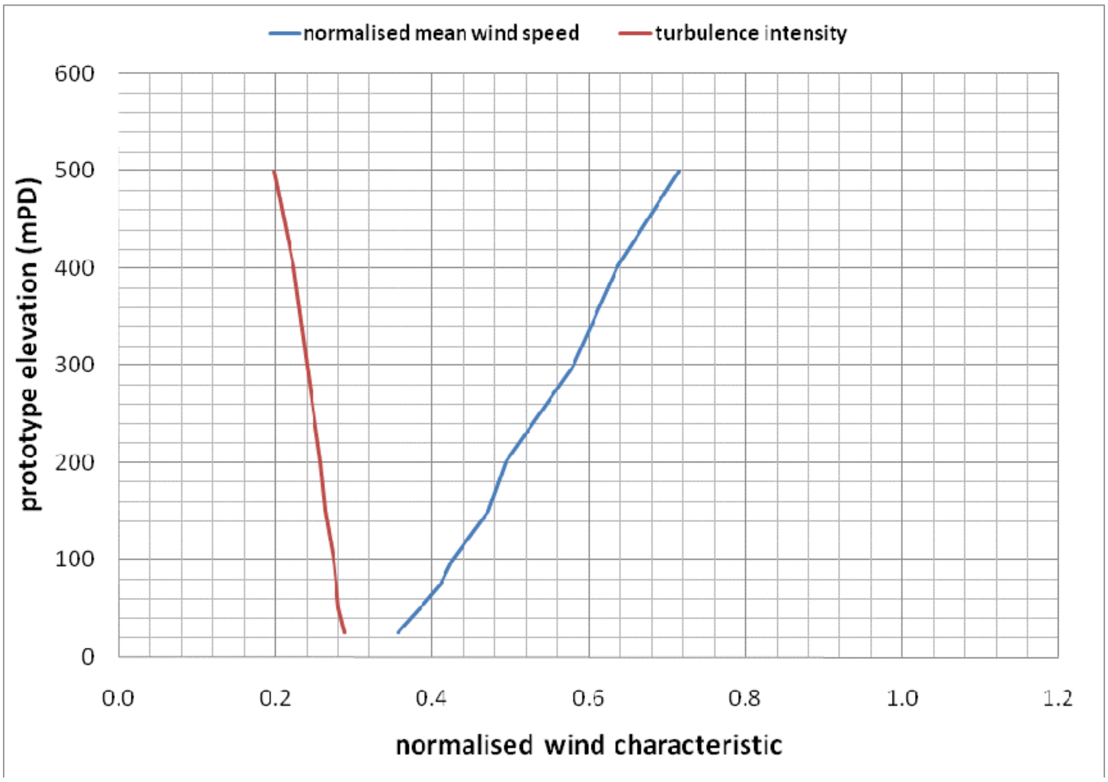

Figure 17a: Wind characteristics for Sha Tin,202.5°

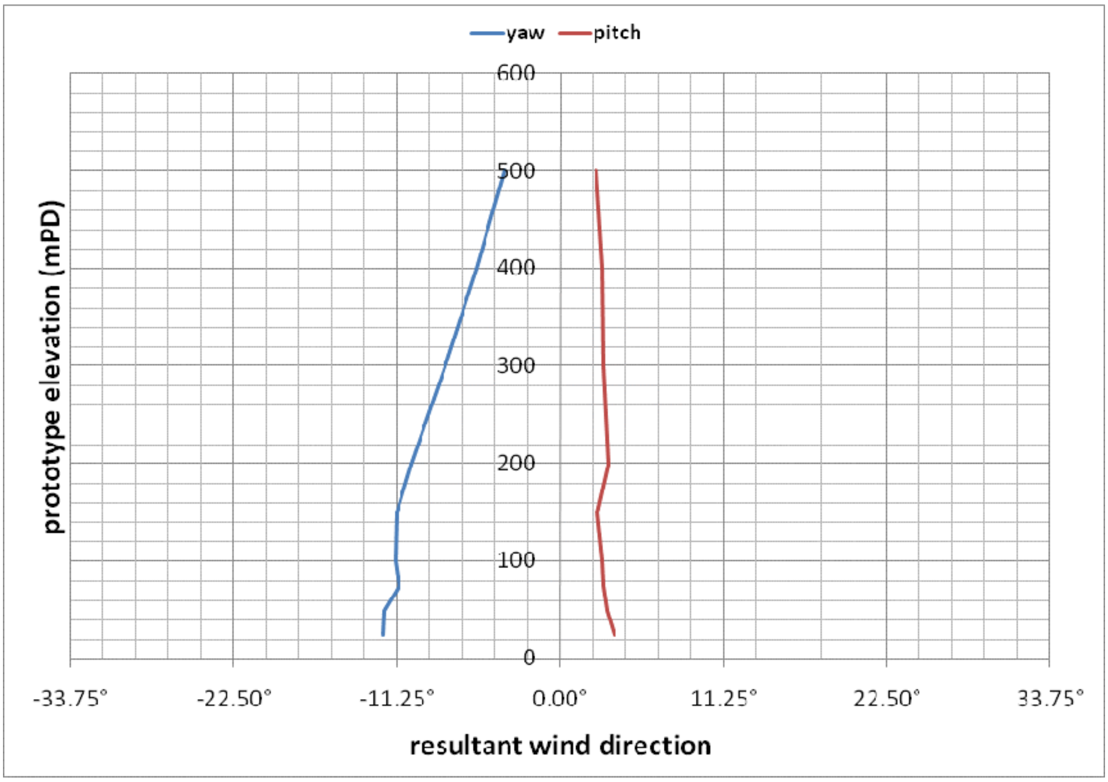

Figure 17b: Mean wind directions for Sha Tin,202.5°

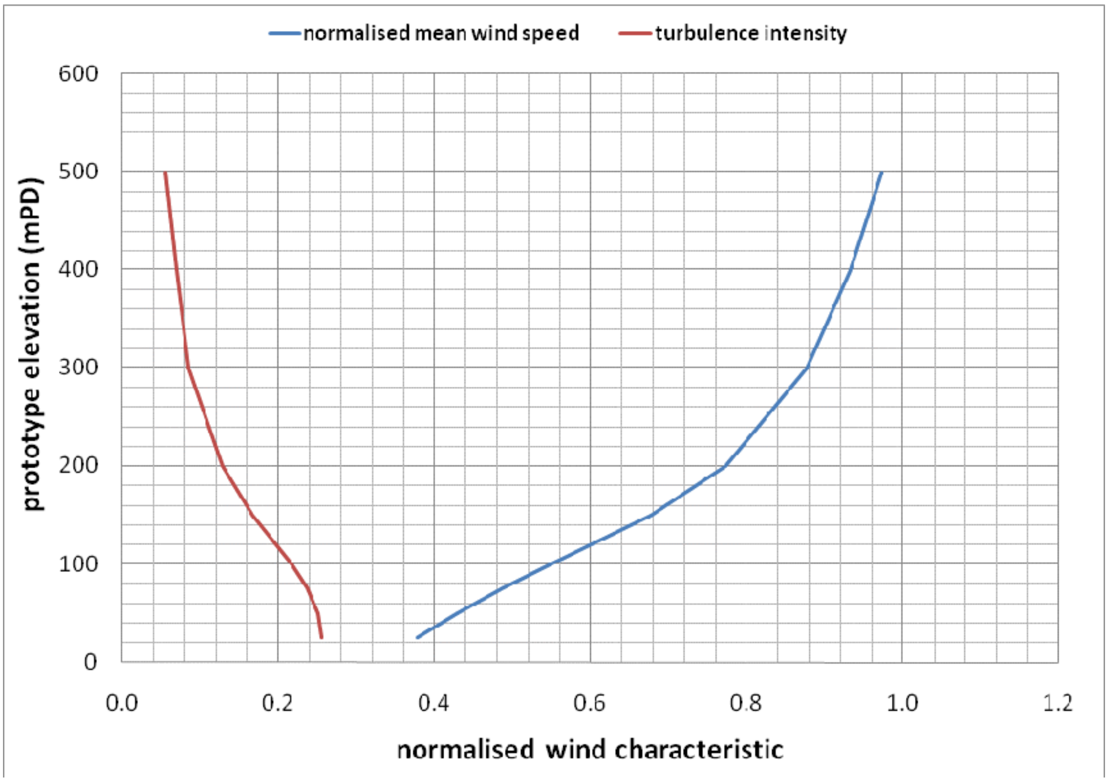

Figure 18a: Wind characteristics for Sha Tin,225°

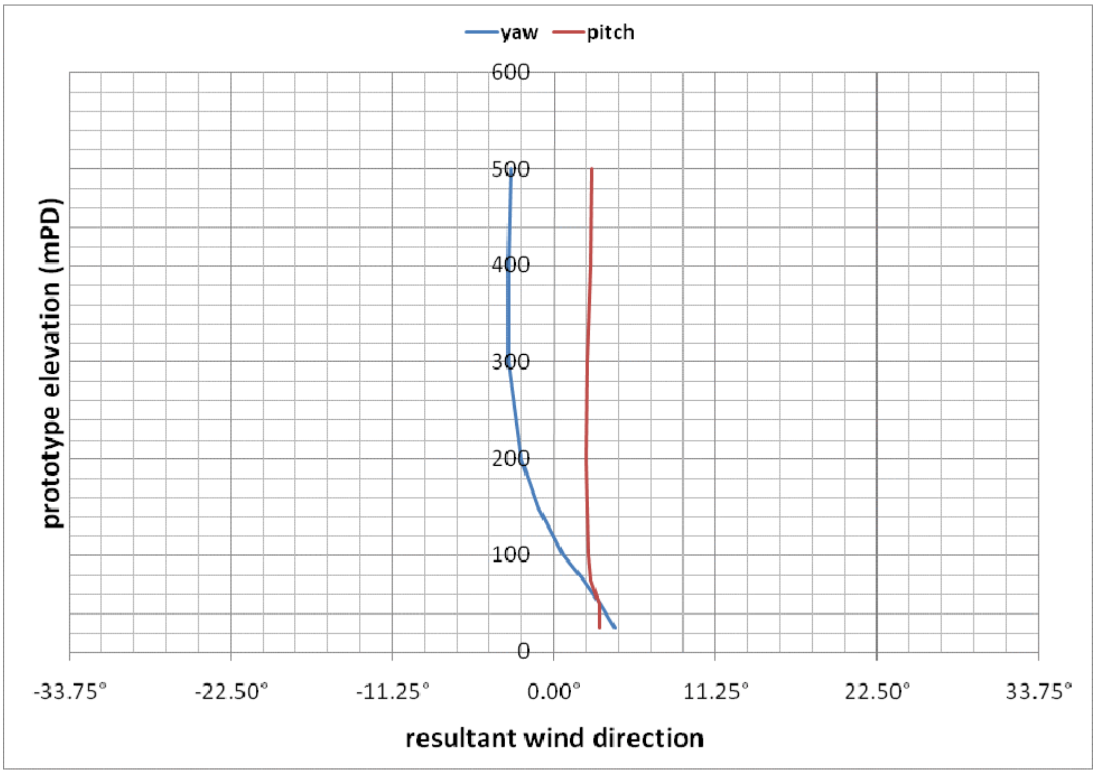

Figure 18b: Mean wind directions for Sha Tin,225°

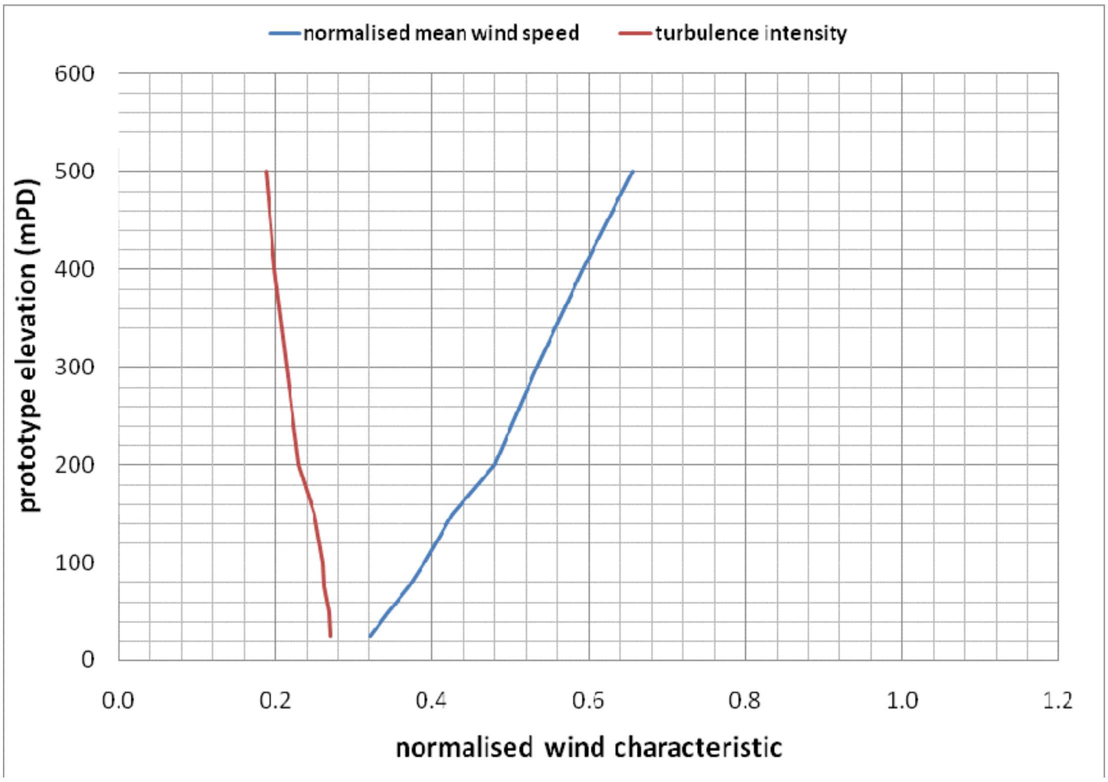

Figure 19a: Wind characteristics for Sha Tin,247.5°

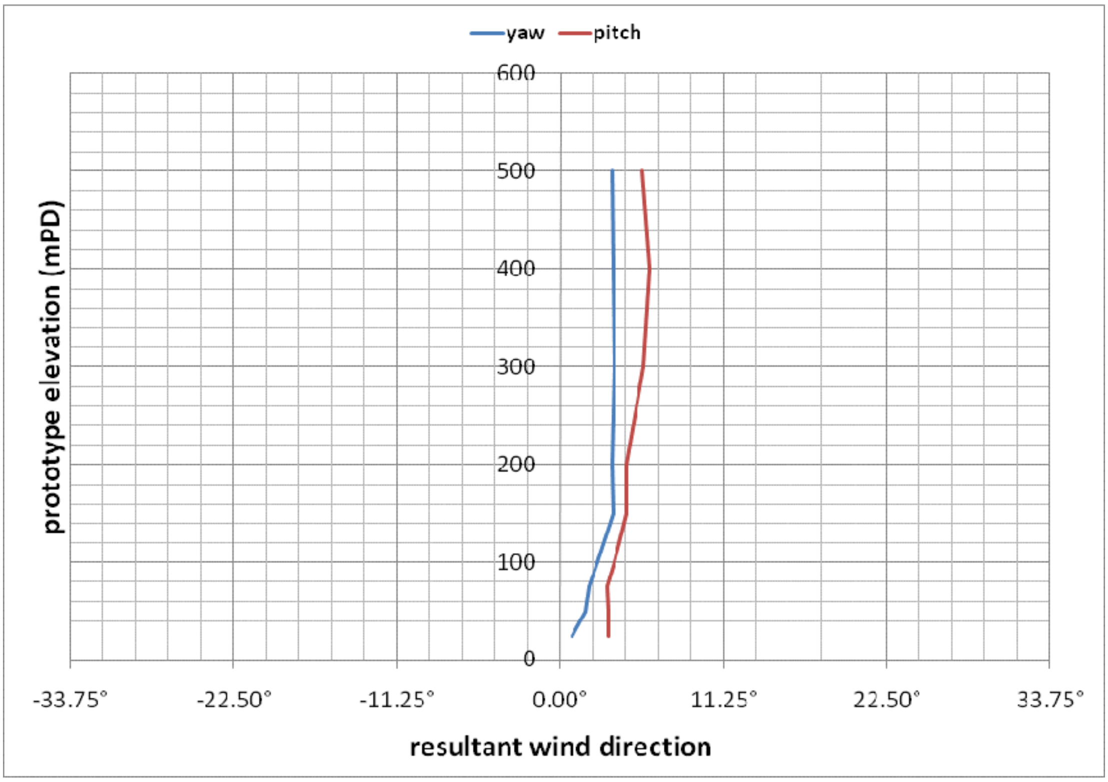

Figure 19b: Mean wind directions for Sha Tin,247.5°

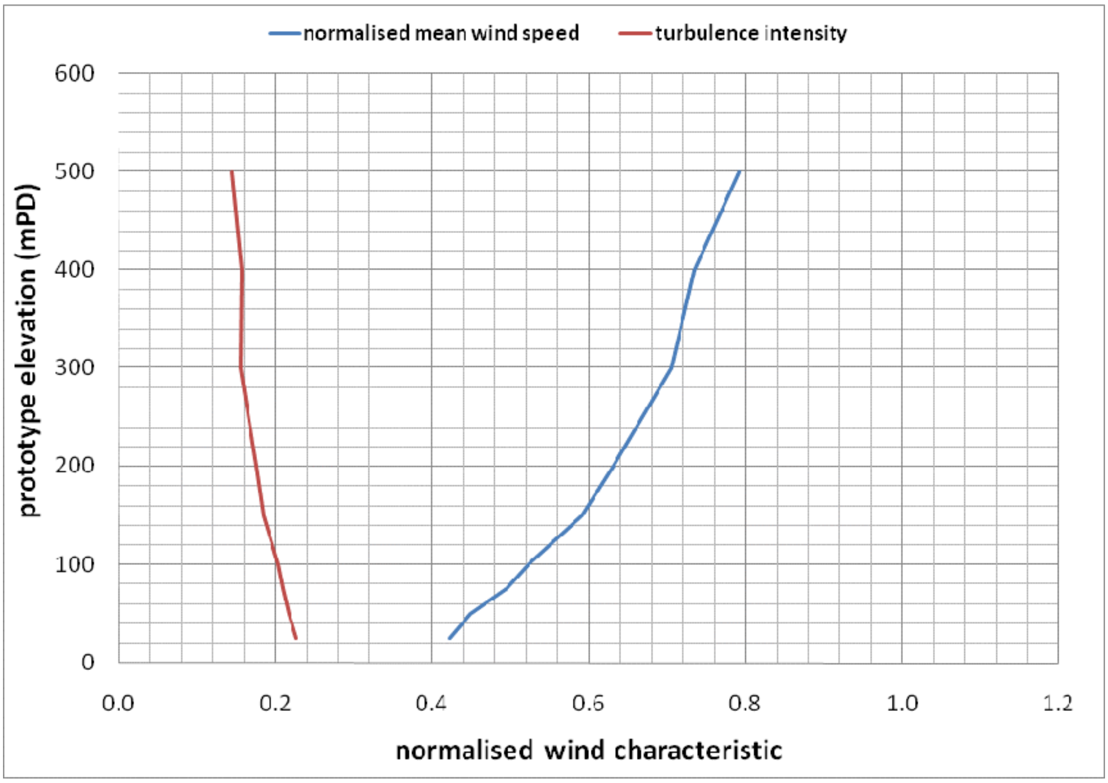

Figure 20a: Wind characteristics for Sha Tin,270°

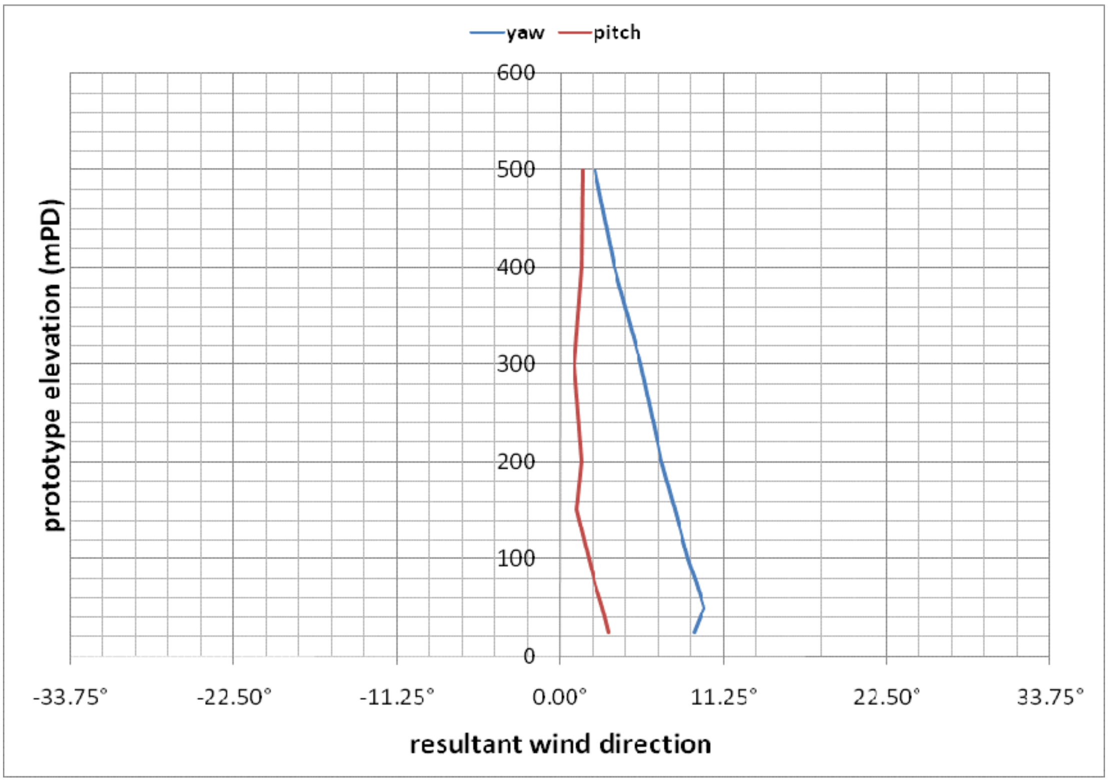

Figure 20b: Mean wind directions for Sha Tin,270°

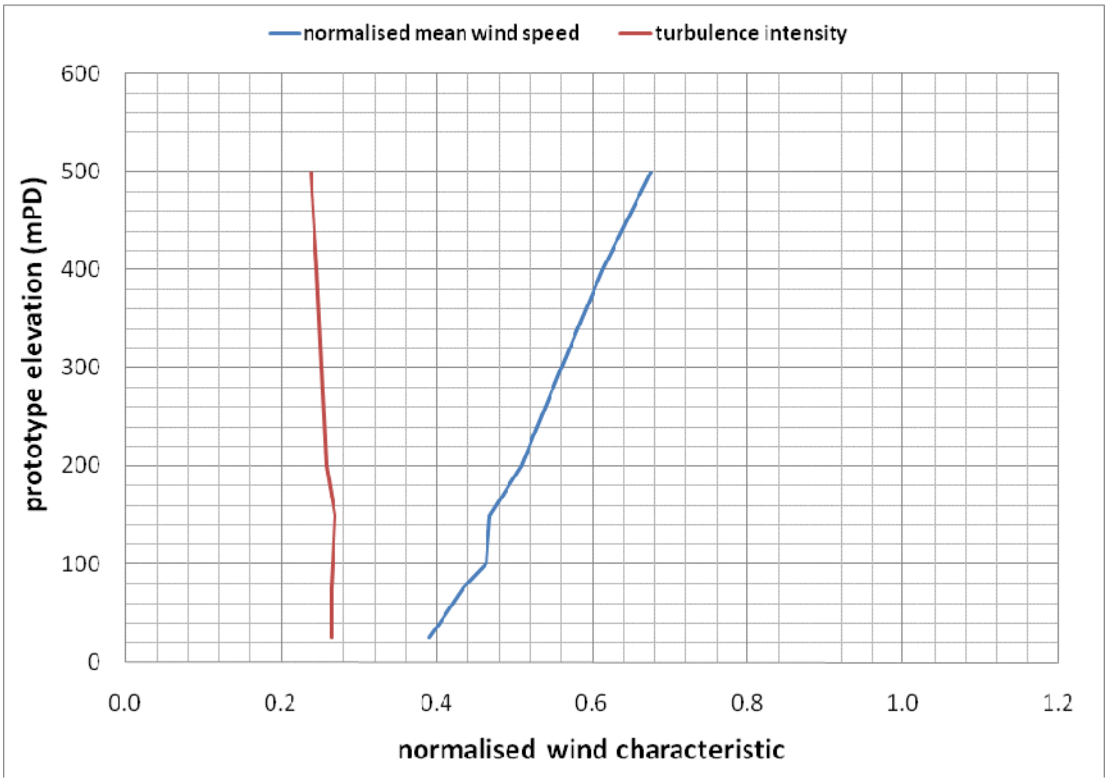

Figure 21a: Wind characteristics for Sha Tin,292.5°

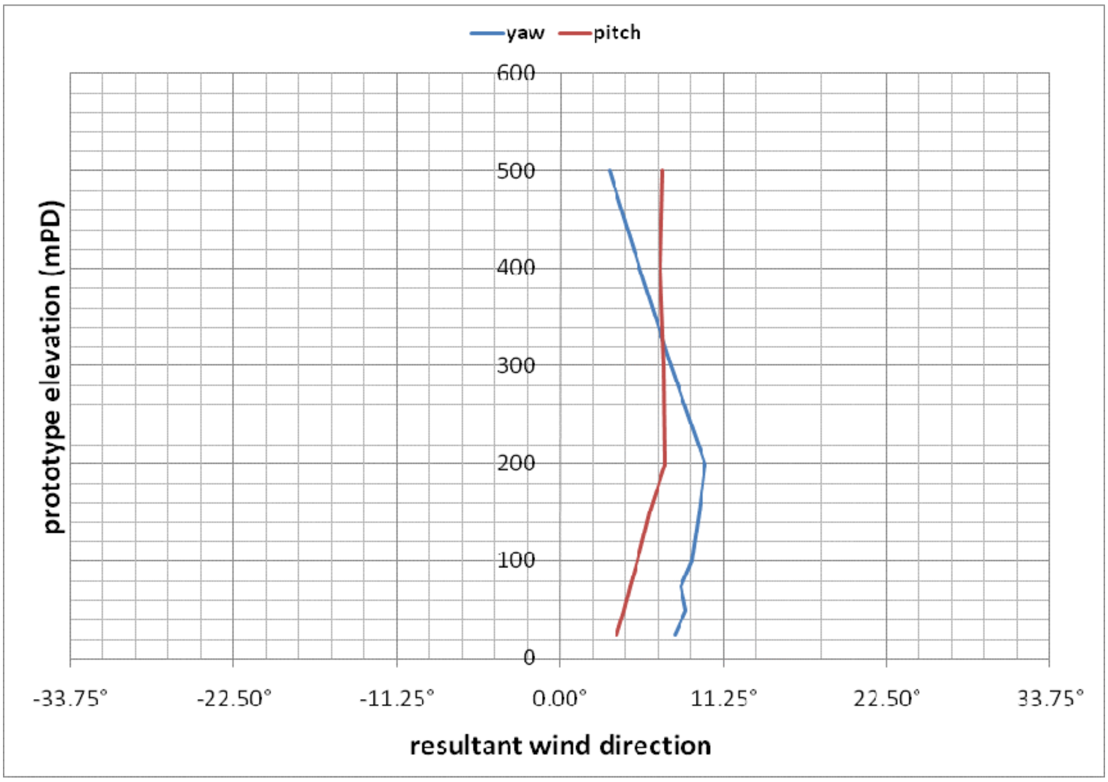

Figure 21b: Mean wind directions for Sha Tin,292.5°

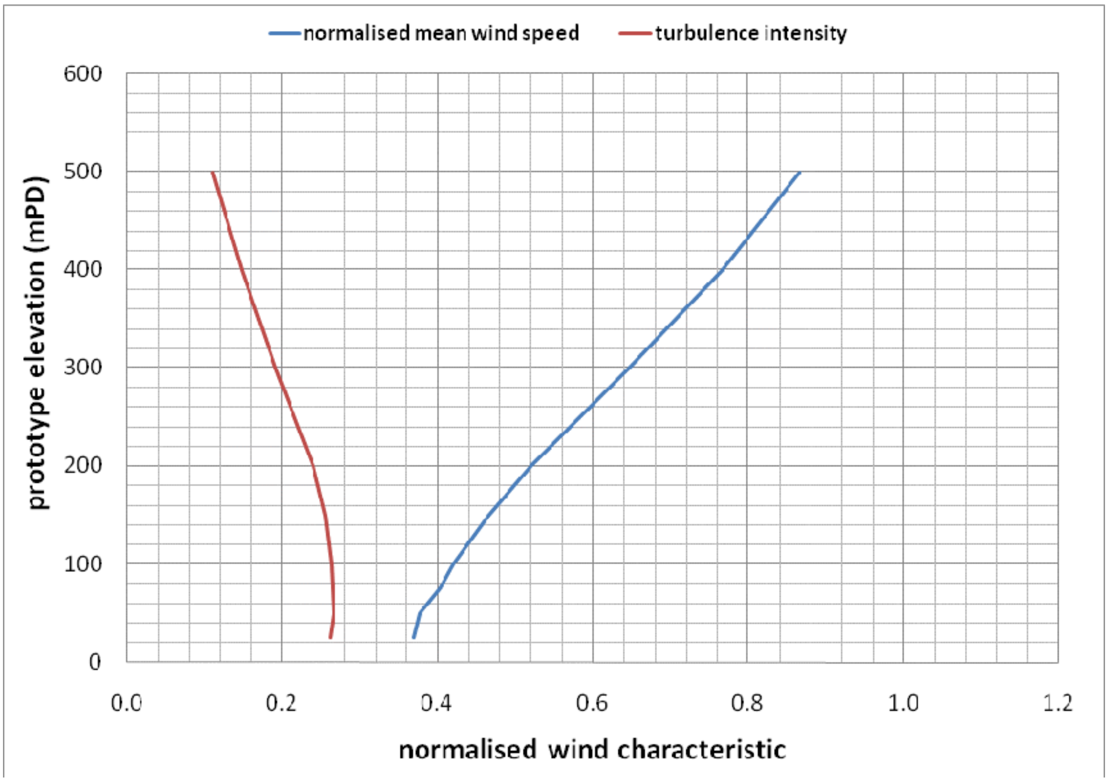

Figure 22a: Wind characteristics for Sha Tin,315°

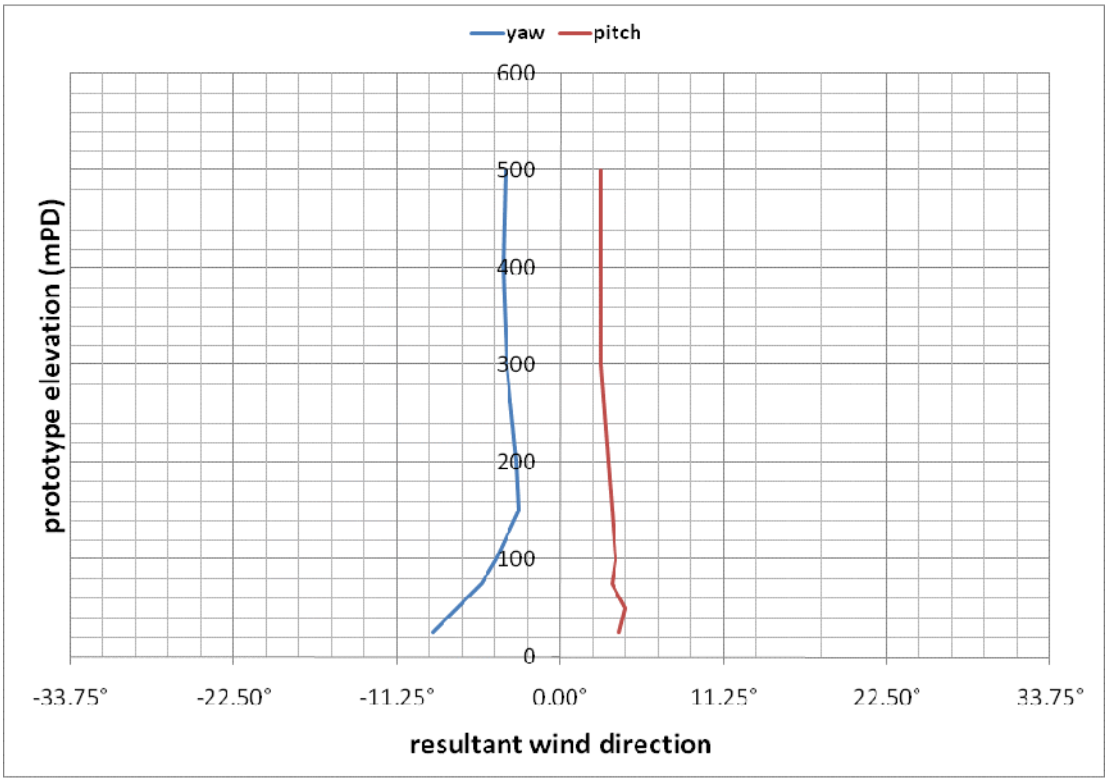

Figure 22b: Mean wind directions for Sha Tin,315°

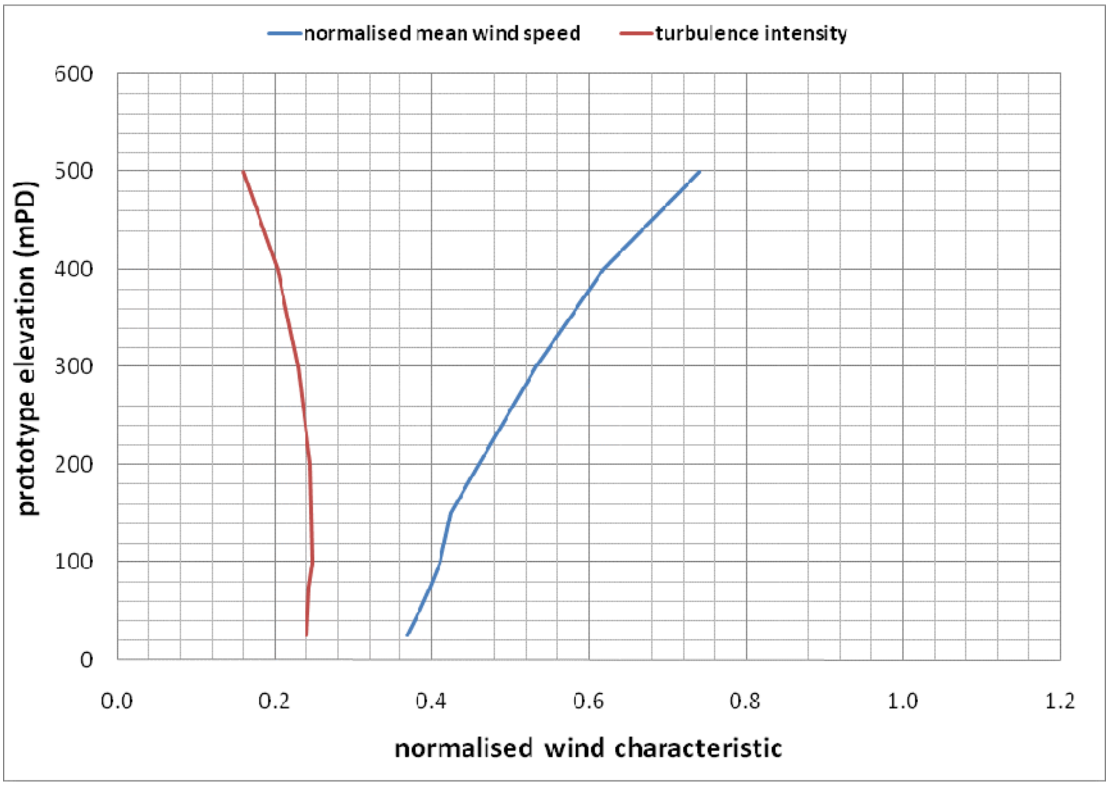

Figure 23a: Wind characteristics for Sha Tin,337.5°

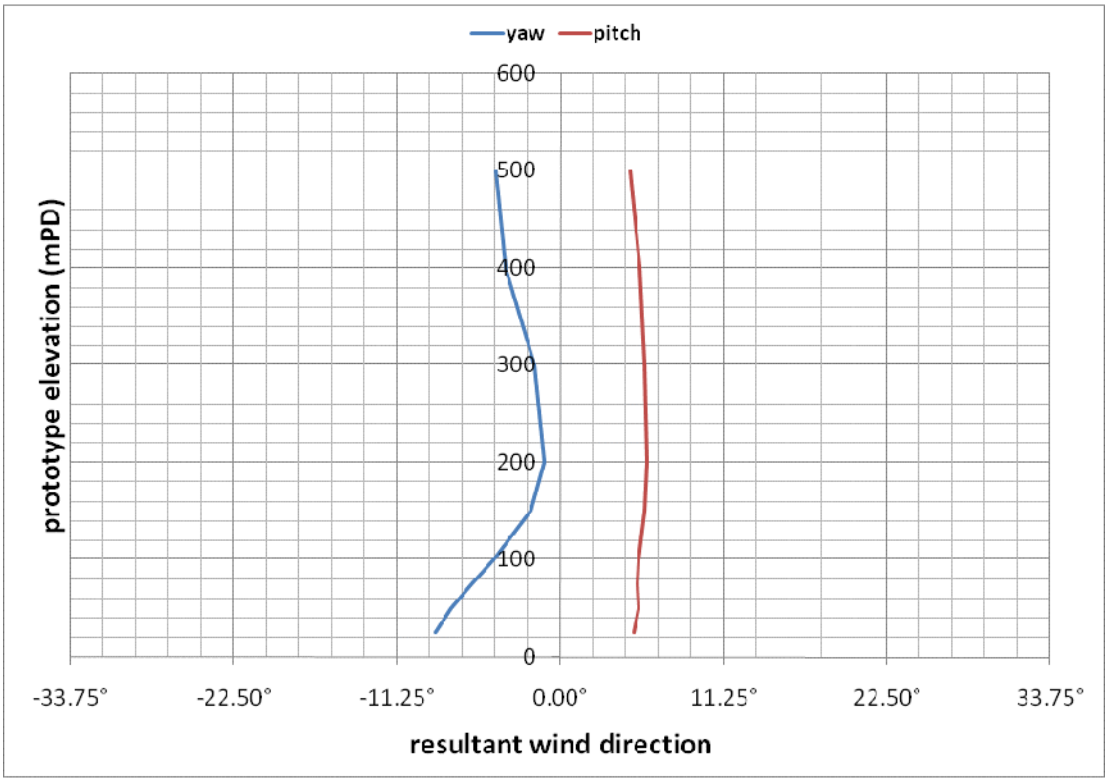

Figure 23b: Mean wind directions for Sha Tin,337.5°

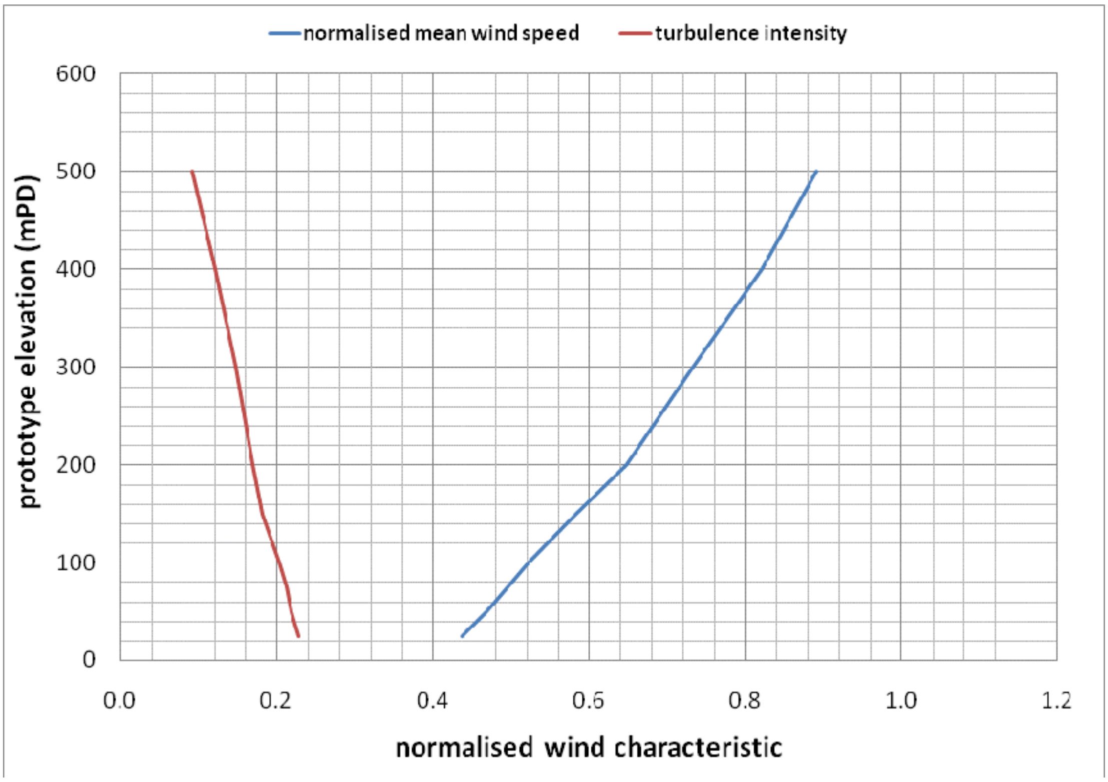

Figure 24a: Wind characteristics for Sha Tin,360°

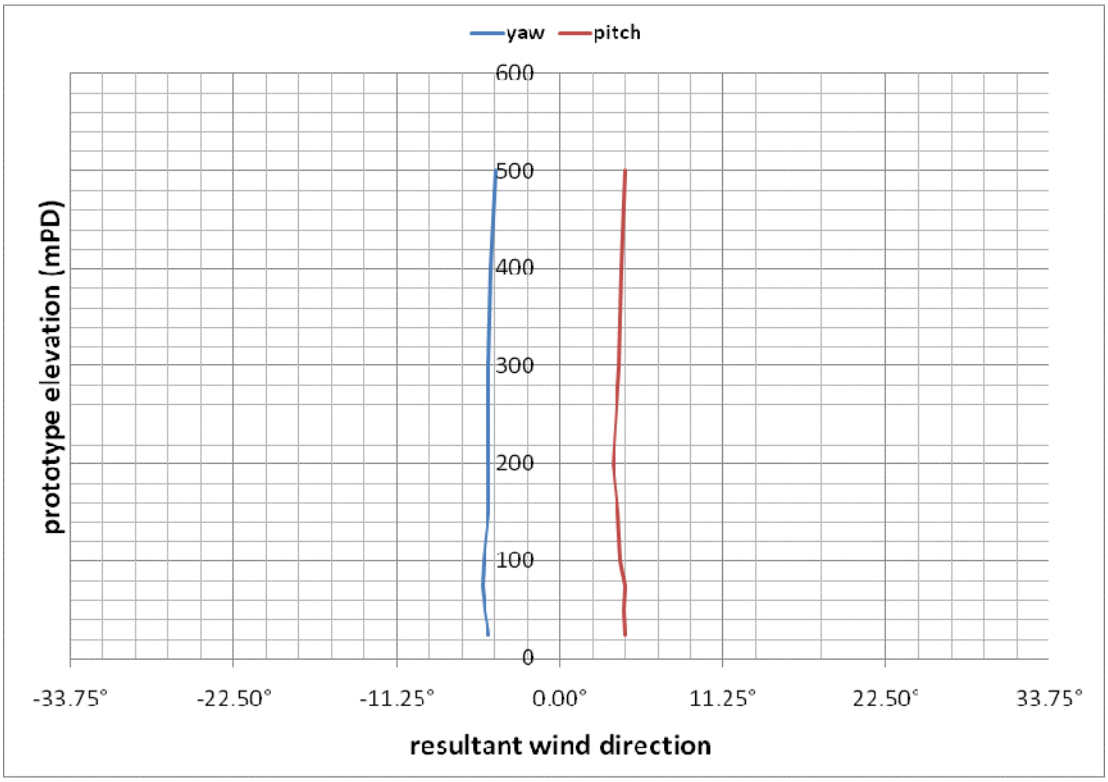

Figure 24b: Mean wind directions for Sha Tin,360°

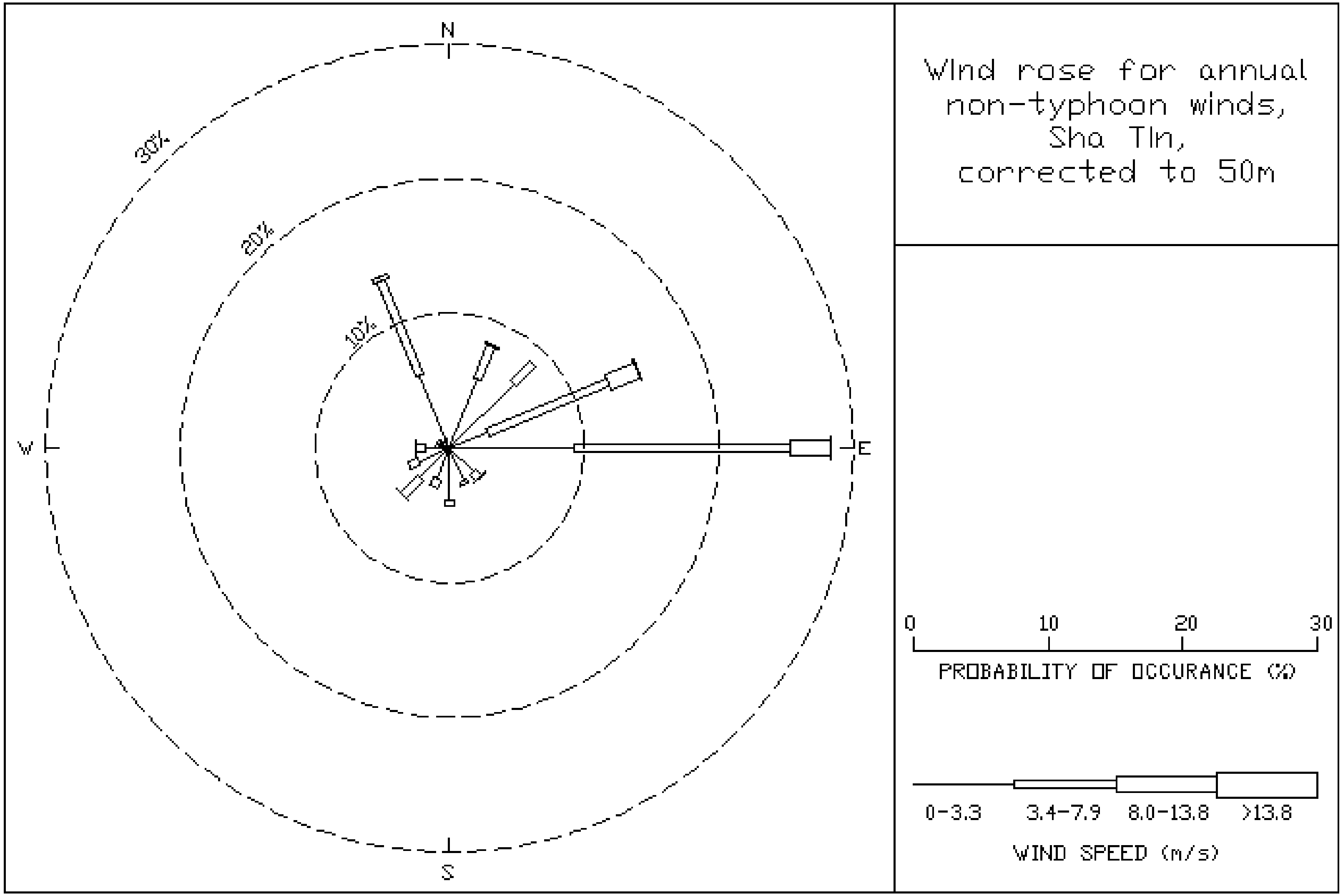

Figure 25: Wind rose for annual, non-typhoon winds for Sha Tin, corrected to 50 mPD

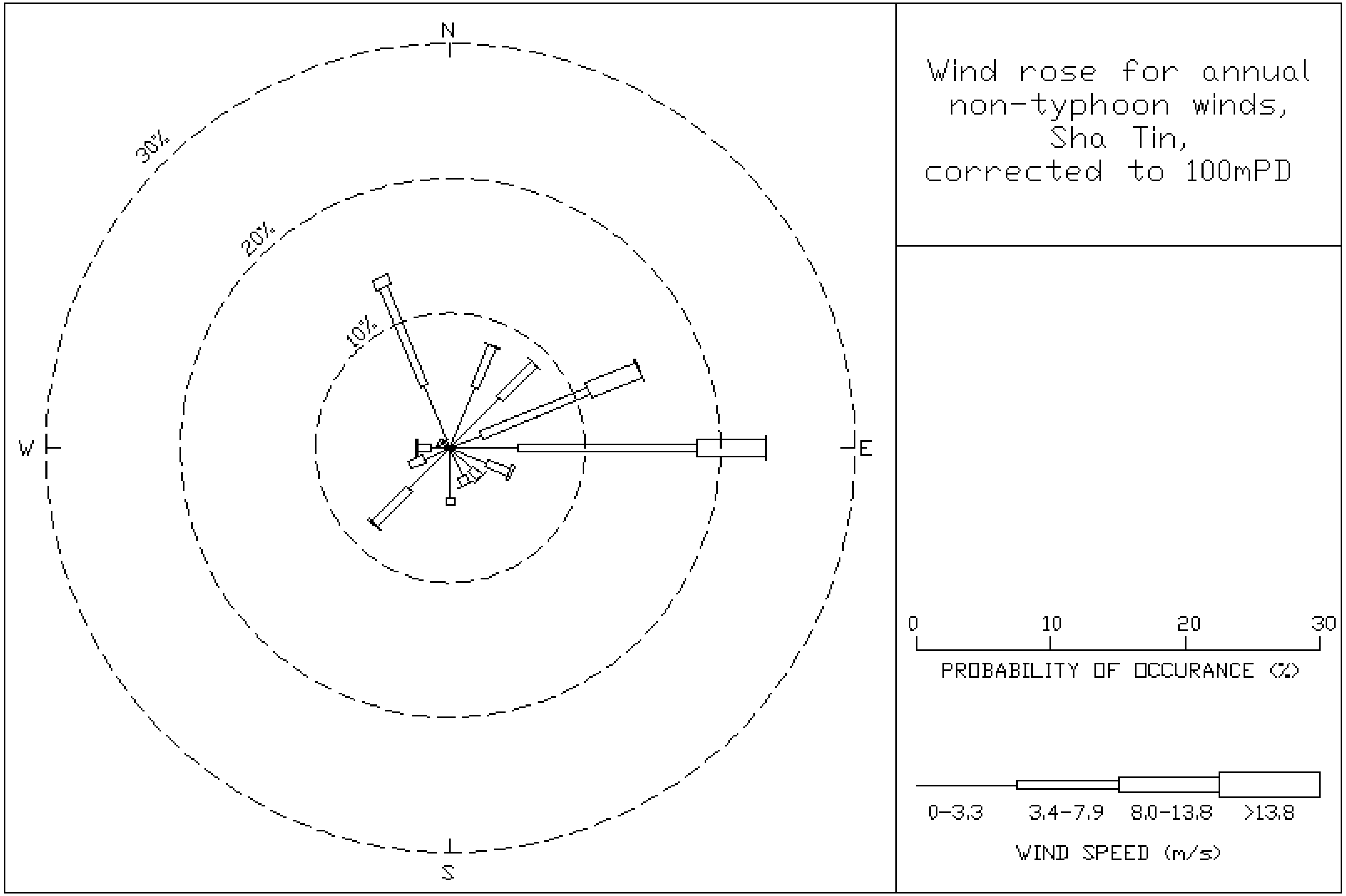

Figure 26: Wind rose for annual, non-typhoon winds for Sha Tin, corrected to 100 mPD

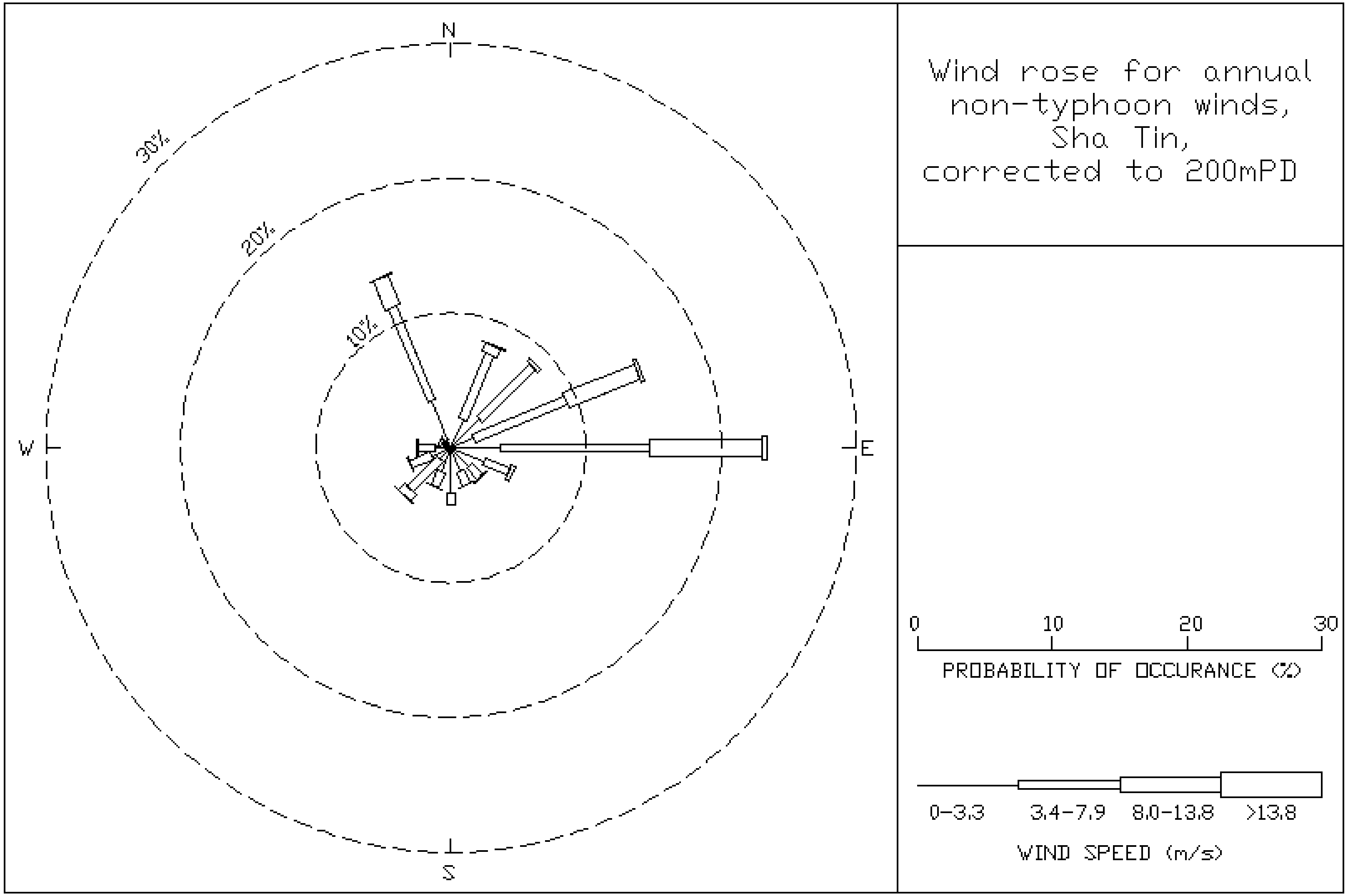

Figure 27: Wind rose for annual, non-typhoon winds for Sha Tin, corrected to 200 mPD

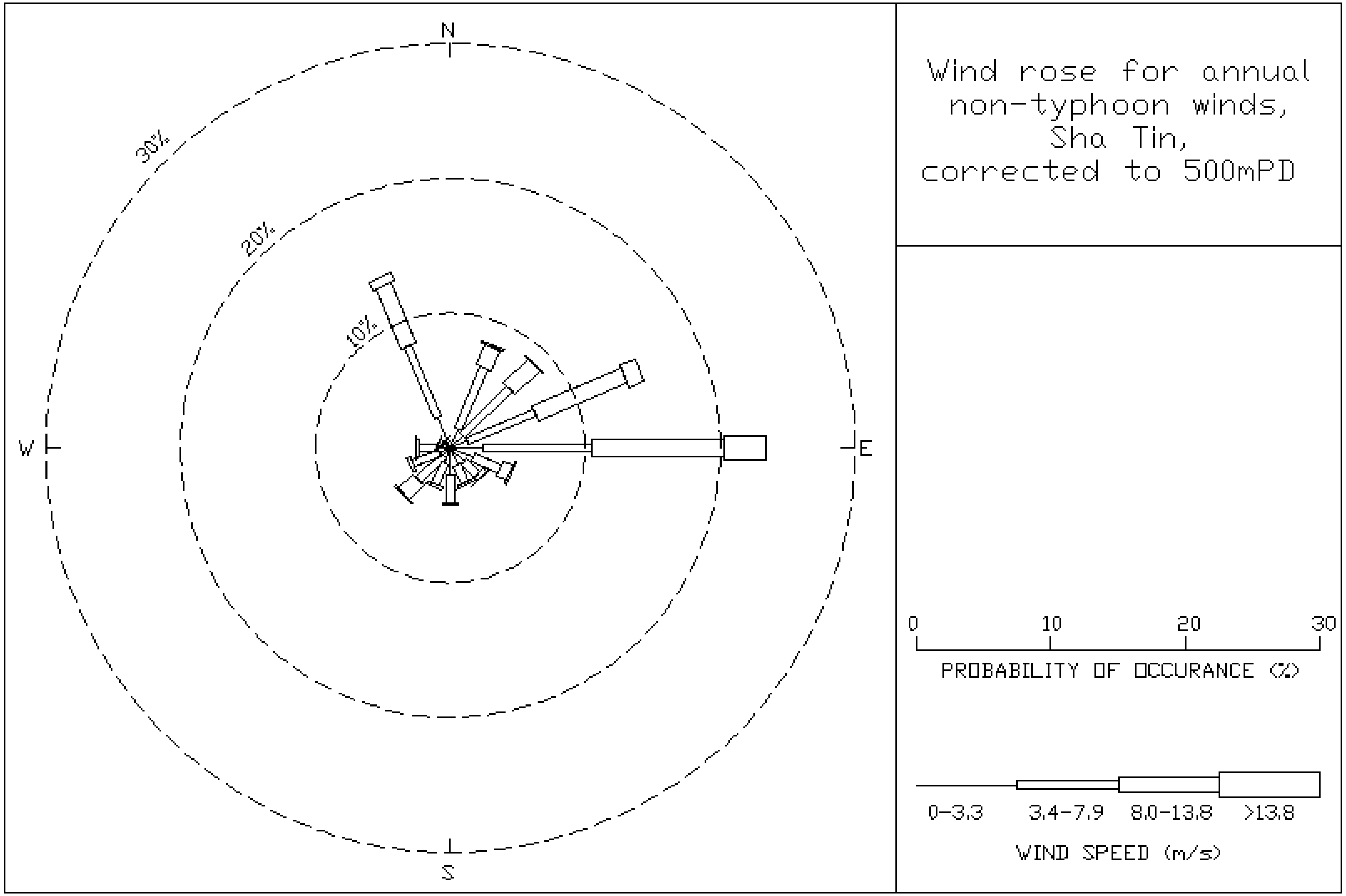

Figure 28: Wind rose for annual, non-typhoon winds for Sha Tin, corrected to 500 mPD

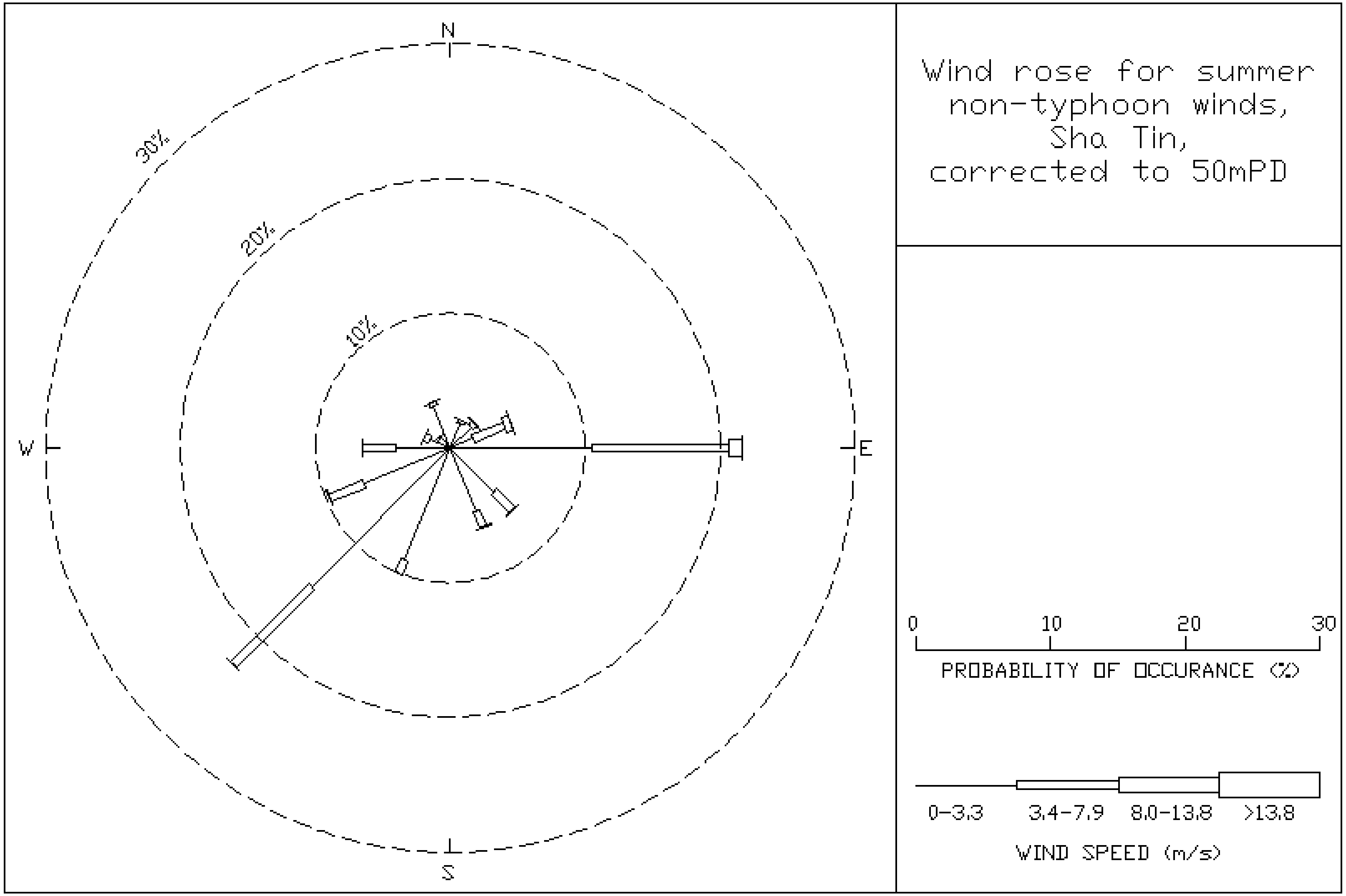

Figure 29: Wind rose for summer, non-typhoon winds for Sha Tin, corrected to 50 mPD

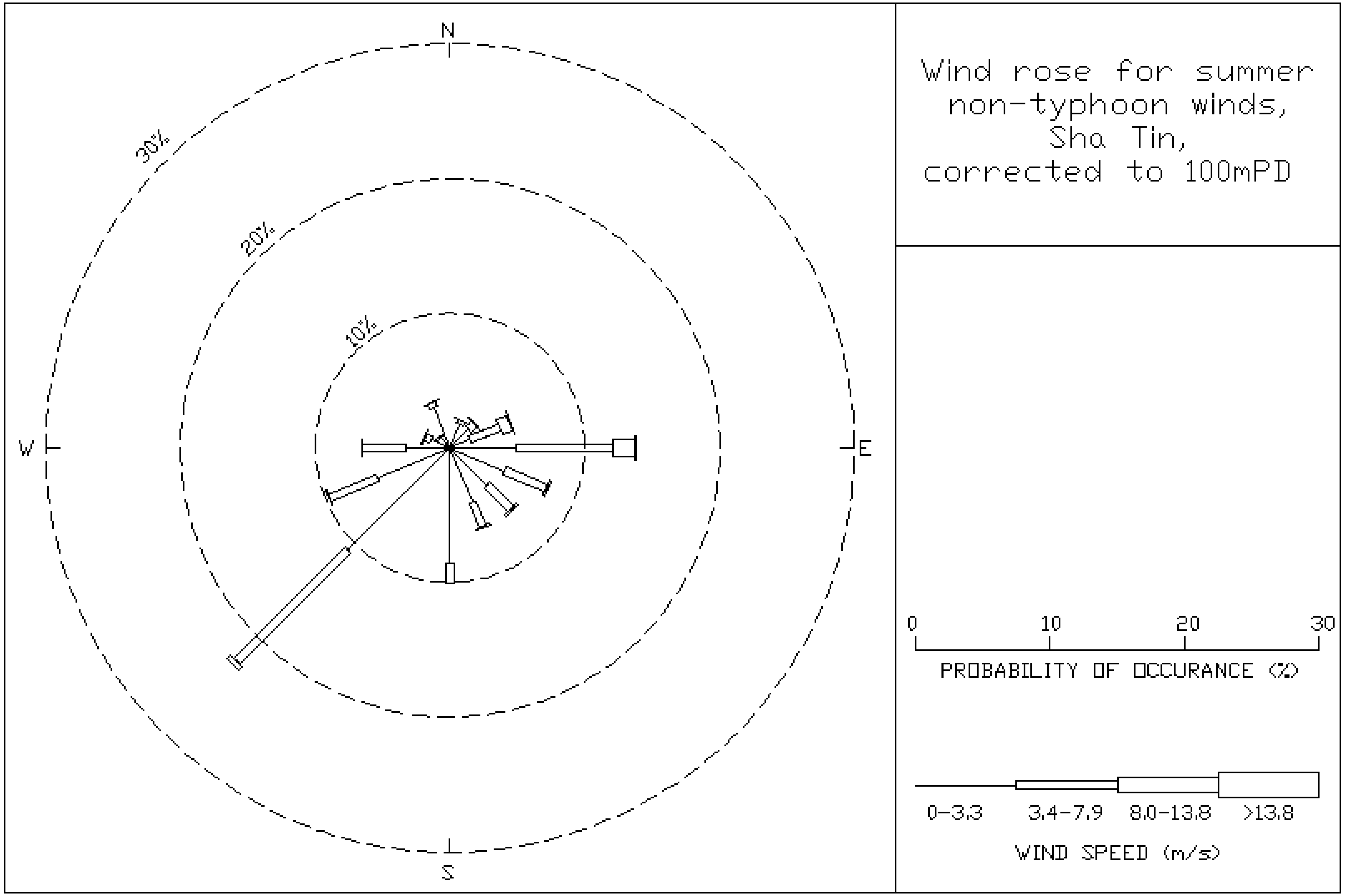

Figure 30: Wind rose for summer, non-typhoon winds for Sha Tin,corrected to 100 mPD

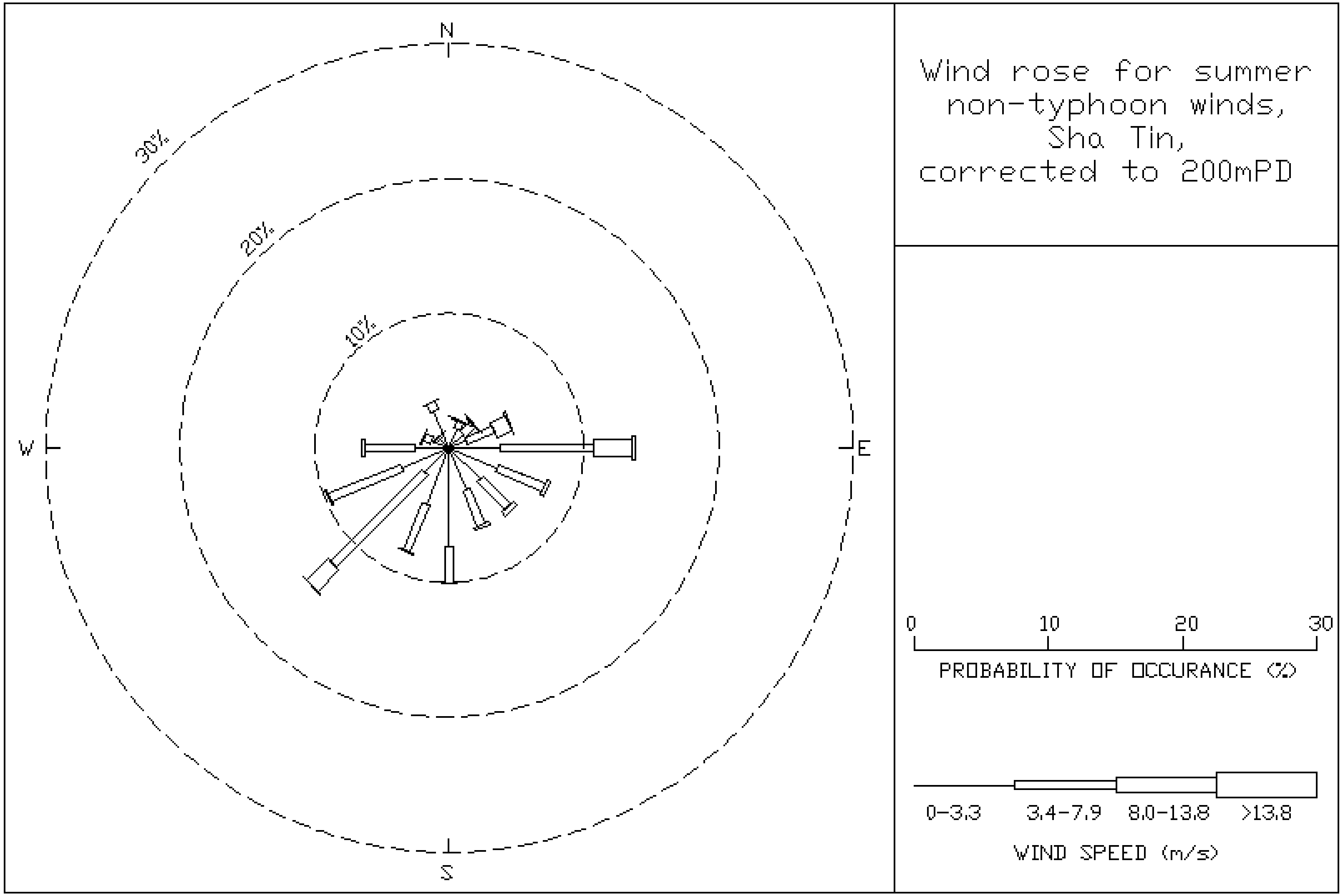

Figure 31: Wind rose for summer, non-typhoon winds for Sha Tin, corrected to 200 mPD

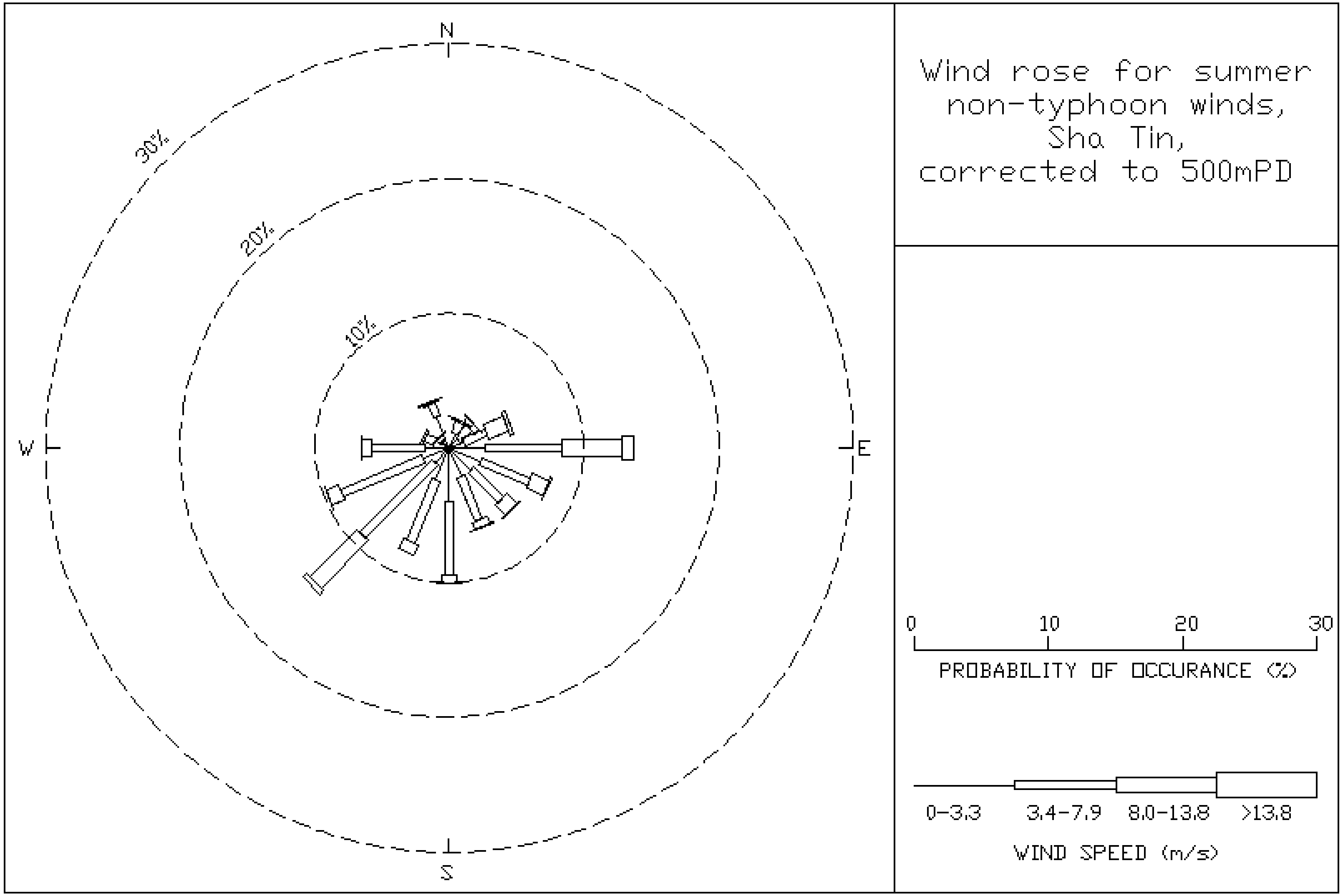

Figure 32: Wind rose for summer, non-typhoon winds for Sha Tin, corrected to 500 mPD

APPENDIX A
TABULATED RESULTS FOR SHA TIN

Table 1: Site wind characteristics of Sha Tin at 22.5°

Prototype scale elevation (mPD)	Normalised mean wind speed	Turbulence intensity (%)	Pitch angle (°)	Yaw angle (°)
25	0.45	21.6%	4.2	-11.9
50	0.45	22.0%	4.2	-9.4
75	0.48	22.0%	4.3	-5.7
100	0.50	21.8%	4.5	-2.6
150	0.62	18.2%	4.6	-1.0
200	0.76	12.1%	4.7	-1.9
300	0.87	6.7%	4.6	-2.6
400	0.92	5.8%	4.3	-2.8
500	0.95	5.1%	4.3	-2.8

Table 2: Site wind characteristics of Sha Tin at 45°

Prototype scale elevation (mPD)	Normalised mean wind speed	Turbulence intensity (%)	Pitch angle (°)	Yaw angle (°)
25	0.36	26.6%	3.6	-12.8
50	0.38	27.2%	3.5	-7.0
75	0.41	26.7%	3.0	-1.4
100	0.46	25.2%	3.3	1.2
150	0.57	20.5%	3.1	2.0
200	0.63	17.9%	3.6	1.9
300	0.76	14.0%	3.3	1.5
400	0.87	10.7%	3.2	0.9
500	0.96	7.4%	3.1	0.5

Table 3: Site wind characteristics of Sha Tin at 67.5°

Prototype scale elevation (mPD)	Normalised mean wind speed	Turbulence intensity (%)	Pitch angle (°)	Yaw angle (°)
25	0.55	22.6%	1.6	1.9
50	0.61	21.3%	0.6	1.6
75	0.65	20.1%	0.0	1.3
100	0.68	19.2%	-0.2	1.0
150	0.74	17.5%	-0.5	0.8
200	0.79	16.0%	-0.5	0.0
300	0.86	13.9%	-0.3	-0.5
400	0.91	12.9%	-0.3	-0.3
500	0.94	12.7%	-0.3	0.2

Table 4: Site wind characteristics of Sha Tin at 90°

Prototype scale elevation (mPD)	Normalised mean wind speed	Turbulence intensity (%)	Pitch angle (°)	Yaw angle (°)
25	0.49	23.0%	2.4	9.1
50	0.53	22.4%	1.7	7.7
75	0.56	21.8%	1.1	7.2
100	0.59	21.1%	0.6	6.3
150	0.67	18.4%	-0.4	5.6
200	0.73	16.6%	-0.7	5.2
300	0.82	13.7%	-1.0	3.8
400	0.89	11.4%	-0.9	2.3
500	0.94	9.7%	-0.4	1.1

Table 5: Site wind characteristics of Sha Tin at 112.5°

Prototype scale elevation (mPD)	Normalised mean wind speed	Turbulence intensity (%)	Pitch angle (°)	Yaw angle (°)
25	0.45	25.8%	1.4	12.2
50	0.49	24.5%	0.6	11.5
75	0.51	24.5%	-0.1	10.9
100	0.52	24.2%	-1.2	8.9
150	0.56	23.9%	-2.1	6.8
200	0.59	23.9%	-2.3	4.6
300	0.66	22.3%	-1.8	1.5
400	0.74	19.3%	-1.2	1.0
500	0.82	16.1%	0.0	0.9

Table 6: Site wind characteristics of Sha Tin at 135°

Prototype scale elevation (mPD)	Normalised mean wind speed	Turbulence intensity (%)	Pitch angle (°)	Yaw angle (°)
25	0.41	25.6%	2.4	-10.4
50	0.47	24.3%	1.4	-10.1
75	0.51	22.9%	1.2	-9.2
100	0.56	21.0%	1.0	-8.3
150	0.62	17.8%	0.6	-6.5
200	0.65	16.4%	0.2	-4.5
300	0.70	15.4%	0.0	-1.2
400	0.79	12.4%	0.1	-0.6
500	0.87	9.6%	0.5	-0.1

Table 7: Site wind characteristics of Sha Tin at 157.5°

Prototype scale elevation (mPD)	Normalised mean wind speed	Turbulence intensity (%)	Pitch angle (°)	Yaw angle (°)
25	0.36	29.2%	-1.4	3.9
50	0.39	25.8%	-1.5	2.9
75	0.41	24.8%	-1.3	1.7
100	0.45	23.9%	-1.1	1.4
150	0.49	21.0%	-1.5	0.2
200	0.57	18.8%	-2.3	-1.1
300	0.61	17.9%	-1.9	-3.8
400	0.69	16.4%	-1.9	-5.2
500	0.78	14.2%	-1.8	-5.4

Table 8: Site wind characteristics of Sha Tin at 180°

Prototype scale elevation (mPD)	Normalised mean wind speed	Turbulence intensity (%)	Pitch angle (°)	Yaw angle (°)
25	0.31	31.1%	0.5	-11.1
50	0.33	31.2%	0.9	-11.3
75	0.34	30.6%	1.4	-11.8
100	0.36	30.9%	1.0	-10.7
150	0.37	30.2%	1.7	-10.0
200	0.41	29.2%	1.2	-7.8
300	0.46	27.3%	1.4	-5.7
400	0.56	24.8%	0.8	-4.6
500	0.65	20.5%	0.5	-4.5

Table 9: Site wind characteristics of Sha Tin at 202.5°

Prototype scale elevation (mPD)	Normalised mean wind speed	Turbulence intensity (%)	Pitch angle (°)	Yaw angle (°)
25	0.35	28.8%	3.7	-12.2
50	0.39	28.0%	3.2	-12.1
75	0.41	27.8%	3.0	-11.1
100	0.44	27.4%	2.9	-11.4
150	0.50	26.3%	2.6	-11.3
200	0.53	25.8%	3.3	-10.3
300	0.61	24.0%	3.0	-8.0
400	0.69	22.4%	2.9	-5.8
500	0.77	19.9%	2.5	-3.9

Table 10: Site wind characteristics of Sha Tin at 225°

Prototype scale elevation (mPD)	Normalised mean wind speed	Turbulence intensity (%)	Pitch angle (°)	Yaw angle (°)
25	0.38	25.5%	3.1	4.2
50	0.43	25.0%	3.1	3.2
75	0.49	23.7%	2.5	2.0
100	0.55	21.7%	2.4	0.6
150	0.68	16.7%	2.3	-1.1
200	0.77	12.8%	2.2	-2.3
300	0.88	8.5%	2.3	-3.2
400	0.93	7.0%	2.5	-3.2
500	0.97	5.6%	2.6	-3.0

Table 11: Site wind characteristics of Sha Tin at 247.5°

Prototype scale elevation (mPD)	Normalised mean wind speed	Turbulence intensity (%)	Pitch angle (°)	Yaw angle (°)
25	0.32	27.0%	3.3	0.8
50	0.34	26.8%	3.3	1.7
75	0.37	26.2%	3.2	2.0
100	0.39	26.0%	3.7	2.5
150	0.42	25.0%	4.5	3.6
200	0.48	23.0%	4.5	3.5
300	0.53	21.4%	5.7	3.7
400	0.59	19.8%	6.1	3.6
500	0.65	18.7%	5.6	3.5

Table 12: Site wind characteristics of Sha Tin at 270°

Prototype scale elevation (mPD)	Normalised mean wind speed	Turbulence intensity (%)	Pitch angle (°)	Yaw angle (°)
25	0.42	22.6%	3.3	9.2
50	0.45	21.6%	2.9	9.9
75	0.49	20.9%	2.4	9.4
100	0.52	20.3%	2.0	8.8
150	0.59	18.4%	1.2	7.9
200	0.63	17.5%	1.5	7.0
300	0.71	15.5%	1.0	5.6
400	0.73	15.6%	1.5	3.7
500	0.79	14.4%	1.6	2.4

Table 13: Site wind characteristics of Sha Tin at 292.5°

Prototype scale elevation (mPD)	Normalised mean wind speed	Turbulence intensity (%)	Pitch angle (°)	Yaw angle (°)
25	0.39	26.5%	3.9	7.9
50	0.41	26.4%	4.4	8.7
75	0.43	26.5%	4.8	8.3
100	0.46	26.6%	5.3	9.1
150	0.47	26.9%	6.1	9.6
200	0.51	25.8%	7.2	10.0
300	0.56	25.2%	7.1	7.7
400	0.61	24.5%	6.9	5.5
500	0.67	23.8%	7.0	3.4

Table 14: Site wind characteristics of Sha Tin at 315°

Prototype scale elevation (mPD)	Normalised mean wind speed	Turbulence intensity (%)	Pitch angle (°)	Yaw angle (°)
25	0.37	26.1%	4.1	-8.8
50	0.38	26.6%	4.5	-7.1
75	0.40	26.5%	3.6	-5.5
100	0.42	26.3%	3.8	-4.5
150	0.47	25.5%	3.6	-2.9
200	0.52	23.9%	3.3	-3.1
300	0.65	19.1%	2.8	-3.7
400	0.77	14.8%	2.8	-4.0
500	0.87	11.1%	2.8	-3.8

Table 15: Site wind characteristics of Sha Tin at 337.5°

Prototype scale elevation (mPD)	Normalised mean wind speed	Turbulence intensity (%)	Pitch angle (°)	Yaw angle (°)
25	0.37	24.1%	5.1	-8.6
50	0.38	24.3%	5.4	-7.5
75	0.40	24.4%	5.3	-6.1
100	0.41	24.9%	5.4	-4.6
150	0.42	24.8%	5.8	-2.0
200	0.46	24.6%	6.0	-1.1
300	0.53	23.1%	5.8	-1.8
400	0.62	20.3%	5.5	-3.8
500	0.74	16.0%	4.8	-4.4

Table 16: Site wind characteristics of Sha Tin at 360°

Prototype scale elevation (mPD)	Normalised mean wind speed	Turbulence intensity (%)	Pitch angle (°)	Yaw angle (°)
25	0.44	22.8%	4.5	-4.9
50	0.47	21.9%	4.4	-5.1
75	0.50	21.3%	4.5	-5.3
100	0.52	20.3%	4.2	-5.2
150	0.58	18.2%	4.0	-4.9
200	0.65	16.9%	3.7	-4.9
300	0.73	14.8%	4.1	-4.9
400	0.82	12.1%	4.3	-4.7
500	0.89	9.2%	4.5	-4.4

Table 17: Percentage occurrence for annual, non-typhoon directional winds at 50mPD

Wind Angle	Percentage occurrence for wind speed ranges:				
	$0 < u \leq 3.3$ m/s	$3.3 < u \leq 7.9$ m/s	$7.9 < u \leq 13.8$ m/s	$u > 13.8$ m/s	Total
0°	0.0%	0.0%	0.0%	0.0%	0.0%
22.5°	5.5%	2.7%	0.1%	0.0%	8.3%
45°	6.7%	2.1%	0.0%	0.0%	8.8%
67.5°	3.1%	9.7%	2.4%	0.0%	15.1%
90°	9.3%	16.0%	3.0%	0.0%	28.3%
112.5°	0.0%	0.0%	0.0%	0.0%	0.0%
135°	2.5%	0.7%	0.0%	0.0%	3.1%
157.5°	2.6%	0.3%	0.0%	0.0%	3.0%
180°	3.9%	0.4%	0.0%	0.0%	4.3%
202.5°	2.4%	0.7%	0.0%	0.0%	3.1%
225°	3.1%	1.9%	0.0%	0.0%	4.9%
247.5°	2.5%	0.8%	0.0%	0.0%	3.2%
270°	1.7%	0.8%	0.0%	0.0%	2.5%
292.5°	0.8%	0.1%	0.0%	0.0%	1.0%
315°	0.6%	0.0%	0.0%	0.0%	0.6%
337.5°	5.8%	7.5%	0.3%	0.0%	13.7%

Table 18: Percentage occurrence for annual, non-typhoon directional winds at 100 mPD

Wind	Percentage occurrence for wind speed ranges:

Angle	0 < u ≤ 3.3 m/s	3.3 < u ≤ 7.9 m/s	7.9 < u ≤ 13.8 m/s	u > 13.8 m/s	Total
0°	0.0%	0.0%	0.0%	0.0%	0.0%
22.5°	4.8%	3.4%	0.1%	0.0%	8.3%
45°	5.2%	3.6%	0.0%	0.0%	8.8%
67.5°	2.4%	8.6%	4.0%	0.1%	15.1%
90°	5.0%	13.3%	5.1%	0.0%	23.4%
112.5°	2.9%	1.8%	0.2%	0.0%	4.9%
135°	2.2%	0.9%	0.0%	0.0%	3.1%
157.5°	2.3%	0.7%	0.0%	0.0%	3.0%
180°	3.8%	0.5%	0.0%	0.0%	4.3%
202.5°	0.0%	0.0%	0.0%	0.0%	0.0%
225°	4.3%	3.7%	0.1%	0.0%	8.1%
247.5°	2.1%	1.1%	0.0%	0.0%	3.2%
270°	1.5%	1.0%	0.0%	0.0%	2.5%
292.5°	0.8%	0.2%	0.0%	0.0%	1.0%
315°	0.6%	0.1%	0.0%	0.0%	0.6%
337.5°	5.0%	8.0%	0.7%	0.0%	13.7%

Table 19: Percentage occurrence for annual, non-typhoon directional winds at 200 mPD

Wind Angle	Percentage occurrence for wind speed ranges:				
	0 < u ≤ 3.3 m/s	3.3 < u ≤ 7.9 m/s	7.9 < u ≤ 13.8 m/s	u > 13.8 m/s	Total
0°	0.0%	0.0%	0.0%	0.0%	0.0%
22.5°	2.3%	5.2%	0.7%	0.0%	8.3%
45°	3.0%	5.6%	0.3%	0.0%	8.8%
67.5°	1.8%	7.3%	5.7%	0.2%	15.1%
90°	3.7%	11.0%	8.2%	0.5%	23.4%
112.5°	2.6%	2.0%	0.3%	0.0%	4.9%
135°	1.9%	1.1%	0.1%	0.0%	3.1%
157.5°	1.9%	1.0%	0.1%	0.0%	3.0%
180°	3.3%	0.9%	0.0%	0.0%	4.3%
202.5°	1.9%	1.2%	0.0%	0.0%	3.1%
225°	1.1%	3.1%	0.7%	0.0%	4.9%
247.5°	1.5%	1.7%	0.0%	0.0%	3.2%
270°	1.2%	1.2%	0.1%	0.0%	2.5%
292.5°	0.7%	0.2%	0.0%	0.0%	1.0%
315°	0.5%	0.1%	0.0%	0.0%	0.6%
337.5°	3.8%	7.6%	2.3%	0.0%	13.7%

Table 20: Percentage occurrence for annual, non-typhoon directional winds at 500 mPD

Wind	Percentage occurrence for wind speed ranges:

Angle	0 < u ≤ 3.3 m/s	3.3 < u ≤ 7.9 m/s	7.9 < u ≤ 13.8 m/s	u > 13.8 m/s	Total
0°	0.0%	0.0%	0.0%	0.0%	0.0%
22.5°	1.5%	4.9%	1.7%	0.1%	8.3%
45°	1.3%	4.9%	2.5%	0.1%	8.8%
67.5°	1.3%	5.4%	7.2%	1.2%	15.1%
90°	2.4%	8.0%	9.8%	3.1%	23.4%
112.5°	1.8%	2.2%	0.8%	0.1%	4.9%
135°	1.4%	1.4%	0.4%	0.0%	3.1%
157.5°	1.4%	1.4%	0.2%	0.0%	3.0%
180°	1.9%	2.1%	0.2%	0.0%	4.3%
202.5°	1.2%	1.7%	0.2%	0.0%	3.1%
225°	0.7%	2.6%	1.5%	0.1%	4.9%
247.5°	0.9%	2.1%	0.3%	0.0%	3.2%
270°	0.9%	1.4%	0.2%	0.0%	2.5%
292.5°	0.6%	0.3%	0.0%	0.0%	1.0%
315°	0.4%	0.2%	0.0%	0.0%	0.6%
337.5°	2.5%	5.8%	4.8%	0.6%	13.7%

Table 21: Percentage occurrence for summer, non-typhoon directional winds at 50 mPD

Wind Angle	Percentage occurrence for wind speed ranges:				
	0 < u ≤ 3.3 m/s	3.3 < u ≤ 7.9 m/s	7.9 < u ≤ 13.8 m/s	u > 13.8 m/s	Total
0°	0.0%	0.0%	0.0%	0.0%	0.0%
22.5°	1.9%	0.2%	0.0%	0.0%	2.2%
45°	2.2%	0.4%	0.0%	0.0%	2.5%
67.5°	1.8%	2.4%	0.5%	0.0%	4.8%
90°	10.5%	10.1%	1.0%	0.0%	21.7%
112.5°	0.0%	0.0%	0.0%	0.0%	0.0%
135°	4.6%	1.9%	0.0%	0.0%	6.5%
157.5°	5.0%	1.3%	0.0%	0.0%	6.4%
180°	0.0%	0.0%	0.0%	0.0%	0.0%
202.5°	9.0%	1.1%	0.0%	0.0%	10.1%
225°	14.5%	8.2%	0.0%	0.0%	22.8%
247.5°	7.0%	2.7%	0.0%	0.0%	9.7%
270°	4.0%	2.5%	0.0%	0.0%	6.5%
292.5°	1.6%	0.4%	0.0%	0.0%	2.0%
315°	1.0%	0.1%	0.0%	0.0%	1.1%
337.5°	3.3%	0.4%	0.0%	0.0%	3.7%

Table 22: Percentage occurrence for summer, non-typhoon directional winds at 100 mPD

Wind Angle	Percentage occurrence for wind speed ranges:				
	0 < u ≤ 3.3 m/s	3.3 < u ≤ 7.9 m/s	7.9 < u ≤ 13.8 m/s	u > 13.8 m/s	Total

0°	0.0%	0.0%	0.0%	0.0%	0.0%
22.5°	1.9%	0.3%	0.0%	0.0%	2.2%
45°	1.9%	0.6%	0.0%	0.0%	2.5%
67.5°	1.6%	2.4%	0.9%	0.0%	4.8%
90°	4.8%	7.3%	1.6%	0.0%	13.8%
112.5°	4.4%	3.3%	0.1%	0.0%	7.9%
135°	3.8%	2.5%	0.1%	0.0%	6.5%
157.5°	4.4%	2.0%	0.0%	0.0%	6.4%
180°	8.6%	1.5%	0.0%	0.0%	10.1%
202.5°	0.0%	0.0%	0.0%	0.0%	0.0%
225°	10.7%	11.7%	0.4%	0.0%	22.8%
247.5°	5.8%	3.8%	0.0%	0.0%	9.7%
270°	3.3%	3.2%	0.1%	0.0%	6.5%
292.5°	1.5%	0.5%	0.0%	0.0%	2.0%
315°	1.0%	0.1%	0.0%	0.0%	1.1%
337.5°	3.2%	0.5%	0.0%	0.0%	3.7%

Table 23: Percentage occurrence for summer, non-typhoon directional winds at 200 mPD

Wind Angle	Percentage occurrence for wind speed ranges:				
	$0 < u \leq 3.3$ m/s	$3.3 < u \leq 7.9$ m/s	$7.9 < u \leq 13.8$ m/s	$u > 13.8$ m/s	Total
0°	0.0%	0.0%	0.0%	0.0%	0.0%
22.5°	1.4%	0.7%	0.1%	0.0%	2.2%
45°	1.4%	1.0%	0.1%	0.0%	2.5%
67.5°	1.3%	2.2%	1.2%	0.1%	4.8%
90°	3.8%	6.9%	2.9%	0.2%	13.8%
112.5°	3.8%	3.7%	0.3%	0.0%	7.9%
135°	3.2%	2.9%	0.4%	0.0%	6.5%
157.5°	3.3%	2.8%	0.2%	0.0%	6.4%
180°	7.4%	2.7%	0.0%	0.0%	10.1%
202.5°	4.5%	3.8%	0.0%	0.0%	8.3%
225°	2.5%	9.6%	2.2%	0.1%	14.5%
247.5°	3.8%	5.7%	0.1%	0.0%	9.7%
270°	2.5%	3.7%	0.3%	0.0%	6.5%
292.5°	1.4%	0.6%	0.0%	0.0%	2.0%
315°	0.9%	0.2%	0.0%	0.0%	1.1%
337.5°	3.0%	0.6%	0.1%	0.0%	3.7%

Table 24: Percentage occurrence for summer, non-typhoon directional winds at 500 mPD

Wind Angle	Percentage occurrence for wind speed ranges:				
	$0 < u \leq 3.3$ m/s	$3.3 < u \leq 7.9$ m/s	$7.9 < u \leq 13.8$ m/s	$u > 13.8$ m/s	Total

0°	0.0%	0.0%	0.0%	0.0%	0.0%
22.5°	1.1%	0.9%	0.1%	0.0%	2.2%
45°	0.9%	1.2%	0.4%	0.1%	2.5%
67.5°	1.1%	1.9%	1.6%	0.3%	4.8%
90°	2.7%	5.8%	4.4%	1.0%	13.8%
112.5°	2.5%	3.9%	1.4%	0.1%	7.9%
135°	2.3%	3.2%	1.0%	0.1%	6.5%
157.5°	2.3%	3.5%	0.6%	0.0%	6.4%
180°	3.9%	5.4%	0.7%	0.0%	10.1%
202.5°	2.6%	4.9%	0.8%	0.0%	8.3%
225°	1.5%	7.6%	4.9%	0.4%	14.5%
247.5°	2.1%	6.6%	1.0%	0.0%	9.7%
270°	1.8%	3.9%	0.8%	0.0%	6.5%
292.5°	1.1%	0.8%	0.1%	0.0%	2.0%
315°	0.7%	0.3%	0.1%	0.0%	1.1%
337.5°	2.5%	1.0%	0.2%	0.0%	3.7%

APPENDIX B

AXIS SYSTEM OF THE COBRA PROBE

The following figures show the standard axis system of the Cobra Probe:

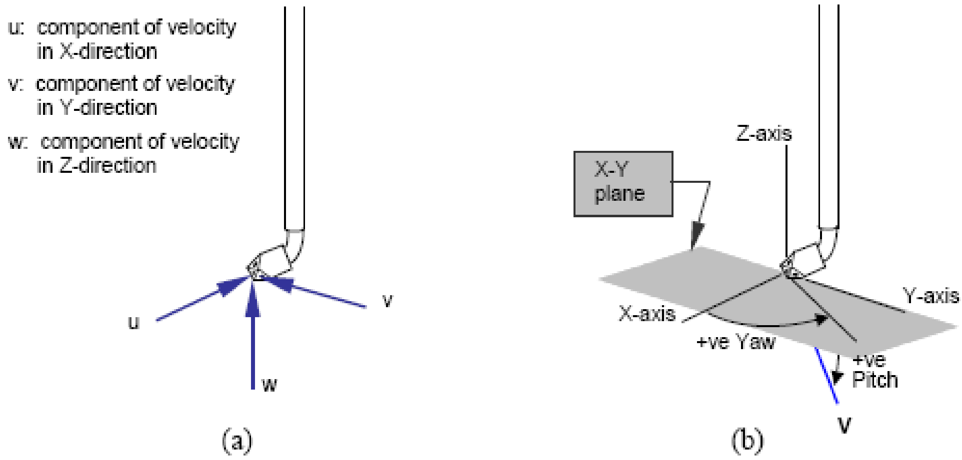

Figure B1: (a) Flow axis system with respect to the Cobra Probe head

(b) Positive flow pitch and yaw angles

Note: Yaw angle is technically 'azimuth' (rotation angle about the z-axis); Pitch angle is technically 'elevation' (the angle between the flow velocity vector V and the X-Y plane).