Site investigation for wind power generation in complex terrain.

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Introduction

Hong Kong is a place without indigenous energy resources such as oil, gas, or coal, and has relied mainly on imported fossil fuels to support its energy requirement. The main objectives of this paper are to advance the understanding of the characteristics of wind flow field in complex, hilly terrain near the coastal region of Hong Kong and to explore the potential for wind power generation. The boundary layer wind tunnel at CLP Power Wind/Wave Facility (WWTF) was used to study the wind flow over the topography of Hong Kong by conducting topographical wind studies using 1:2000 scale models of the Hong Kong SAR. The test results were used to identify typical landscape features with the potential for wind power generation. Selected locations, including mountain tops and an outlying island, were identified for detailed study. Progressive acceleration of the wind velocity profile was observed as wind advanced along the upwind slope of a topographical feature in excess of 700 m in height. The resultant significant wind speedup effects were combined with the wind records collected at a nearby meteorological station to estimate the wind power budget, with which the potential for wind power generation was assessed.

Wind Climate in Hong Kong

The meteorological records obtained from Hong Kong Observatory clearly show that there are two predominant meteorological phenomena at work. During the months of May to October, typhoons are common in the region, and it is these winds that buildings and structures in Hong Kong must be designed to resist. However, these relatively infrequent, intense storms should not be the primary basis for estimating wind power potential in Hong Kong. Therefore, the current investigations concentrate on developing site-specific statistical wind models based on non-typhoon winds only.

Selection of meteorological stations

Long-term variability in wind speed and wind direction can have significant implications for wind power resources and it is essential to assess these to determine the viability of potential sites. In order to make reliable estimates of wind resources, it is preferable that wind data covering a period of at least 5 years [1] be used in an analysis of wind characteristics for a particular site. In general, an annual average hourly mean wind speed greater than 4 m/s is required for the economical operation of small wind turbines [2]. It is generally uneconomical to operate wind turbines in areas of higher wind speed but with relatively low frequency of occurrence.

Over the past 30 years, the Hong Kong Observatory has established thirty-eight meteorological stations with instrumentation for the measurement and recording of wind data at various locations in Hong Kong, although many of these have been operating for less than 5 years. As sustained wind speed is the one of the most important criteria for selecting suitable wind power sites, several meteorological stations satisfying the criteria for the minimum data period and sustained wind speed were selected for detailed investigation, and they are listed in Table 1.

Table 1. Selected meteorological stations.

Station	Terrain Type	Data Period	Ave. hourly mean wind speed (m/s)	Anemometer height above sea level (m)
Yi Tung Shan (YTS)	Hilltop	1997-2003	7.35	752.2
Tai Mo Shan (TMS)	Hilltop	1987-2003	6.9	968.57
Waglan Island (WI)	Offshore	1975-2003	6.48	82
Green Island (GI)	Offshore	1989-2003	5.8	105

These four meteorological stations are located at well-exposed locations, as shown in Fig. 1.

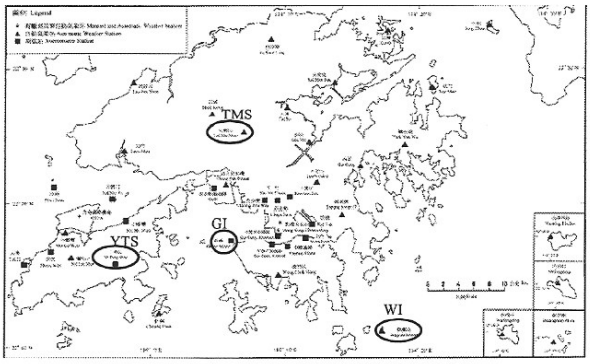


Fig. 1 Locations of meteorological stations

Data at Yi Tung Shan meteorological station

Wind Speed

Yi Tung Shan(YTS), part of a mountain range located on Lantau Island, was investigated in detail to assess the local wind conditions and their suitability for wind power generation. Wind data collected from Yi Tung Shan meteorological station between 1997 and 2003 was analysed. The wind data was sorted in increments of 1 m/s and normalized by the total number of observations. The sum of all the normalized observations, otherwise called the probability density function, is unity. A histogram of the wind speed distribution at YTS, and the corresponding Weibull distribution, is shown in Fig.2.

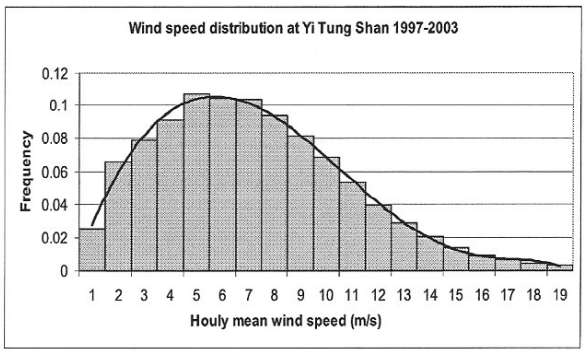


Fig. 2 Distribution and Weibull probability function for wind speed at YTS.

The Weibull probability function is generally considered to provide a good approximation of the distribution of the wind speed over time for synoptic wind phenomena and is given by:

$$P(v)=\frac{k}{c}(\frac{v}{c})^{k-1}\exp\{-(\frac{v}{c})^{k}\} \qquad (1)$$

Where $P(v)$ is the frequency of occurrence of a wind speed v; k is a dimensionless shape parameter; and c is a scale parameter, in m/s. The cumulative probability distribution is given by:

$$P(>v) = \exp\{(\frac{v}{c})^{k}\} \qquad (2)$$

The Weibull shape parameter and the scale parameter for YTS were found to be 2.1 and 8.56 m/s respectively. Based on this analysis, between 1997 and 2003, the hourly mean wind speed at Yi Tung Shan exceeded 4m/s for approximately 81% of the time. The wind speed data and the Weibull parameters will be used for further investigation to estimate the wind power output for a specific wind turbine at YTS.

Wind direction

The prevailing wind directions are important for the siting of wind turbines, and the wind data were further sorted according to wind direction to produce the directional distribution of wind speed as shown in Fig.3.

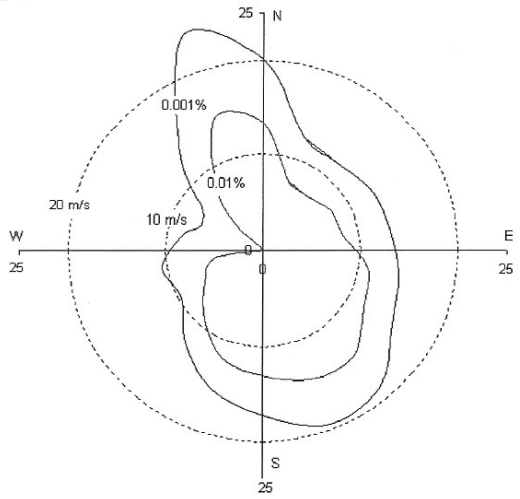


Fig. 3 Directional characteristics of wind at Yi Tung Shan for 1997 to 2003

The prevailing non-typhoon wind directions at YTS are approximately north-north-west and south-south-east and are largely influenced by the local topography. This differs significantly, though not unexpectedly, to the prevailing wind directions determined from a previous analysis of data collected at the isolated Waglan Island [3] and which is generally considered to be representative for winds approaching Hong Kong.

Wind tunnel topographical study of YTS

A topographical study of Yi Tung Shan was conducted in the 5m wide, 4 m high and 40 m long low-speed section at the CLP Power Wind/Wave Tunnel Facility. The topography within 3 km of Yi Tung Shan was modeled at contour intervals of 20 m and was terraced to represent the roughness of mountainous terrain of Lantau Island.

The HKSAR's Building Department publication, PNAP 150 (1994) [4] provides guidance for wind tunnel model testing of buildings in Hong Kong for the purposes of determining wind-induced loads and responses, including profiles for wind flow over two terrain categories, namely: general terrain and built-up terrain. However, these profiles are not necessarily the most suitable for wind power investigations. As an alternative, an approach wind model representative of non-typhoon wind conditions

was simulated in the test section for the topographical model study. The simulations included appropriate modeling of the wind velocity profile, turbulence intensity profile and longitudinal turbulence spectrum to match the length scale of 1:2000 of the topographical model. The target wind model was based on an open terrain category 2 with a roughness height of 0.02 m as suggested in the Australian/New Zealand Standard AS/NZS 1170.2:2002 [5]. The gust wind speeds specified in AS/NZS 1170.2:2002 can be converted to equivalent mean wind speeds according to the relationship:

$$\hat{U} = \overline{U}(1 + gI_u) \qquad (3)$$

where $\hat{U}$ is the gust wind speed, $\overline{U}$ is the mean wind speed, I_u is the turbulence intensity, and g is the peak factor which was assumed to be 3.7 as suggested in AS/NZS 1170.2:2002 [5]. The mean wind speed and turbulence intensity profile of PNAP150 general terrain and category 2 AS/NZS 1170.2:2002 are compared in Fig. 4.

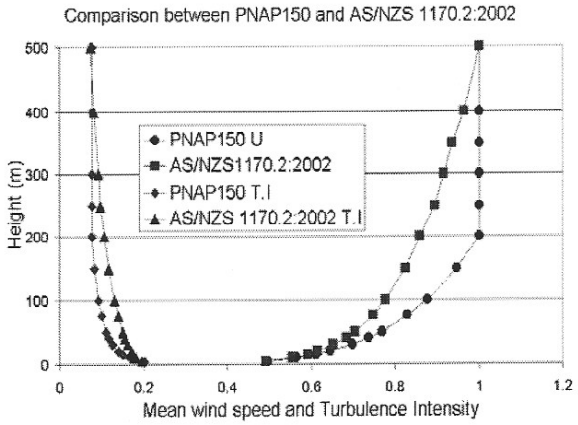


Fig. 4. Comparison between PNAP150 and AS/NZS 1170.2:2002

Preliminary wind tunnel study results

A TFI ECA multi-hole pressure probe was used to simultaneously measure the three components (u, v and w) of wind velocity and the corresponding turbulence intensities. Wind tunnel measurements were taken at 20° intervals for the full 360° azimuth at the YTS meteorological station. The directional mean wind speeds, measured at a height equivalent to 20 m and normalized with respect to the approach mean wind speed at 20 m, are shown in Fig.5.

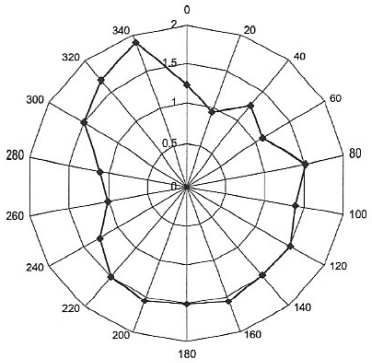
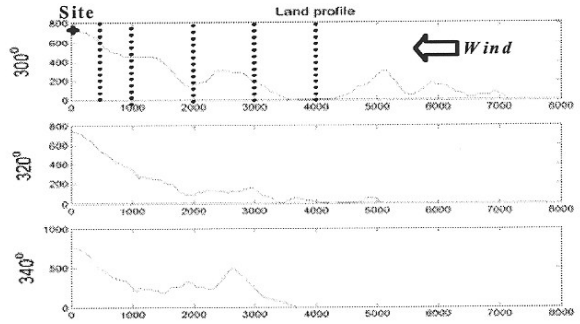


Fig. 5. Directional mean wind speed at YTS.

Comparing Fig.3 & Fig.5, the results indicate that the directional mean wind speeds at YTS are dominated by topographical effects. The prevailing wind directions at YTS were also identified for further studies and included wind directions of 300°, 320°, and 340°, designated as north-westerly (NW) winds, and 120°, 140°, and 160°, designed as south-easterly (SE) winds.

Detailed directional investigation

North-westerly (NW)



South-Easterly (SE)

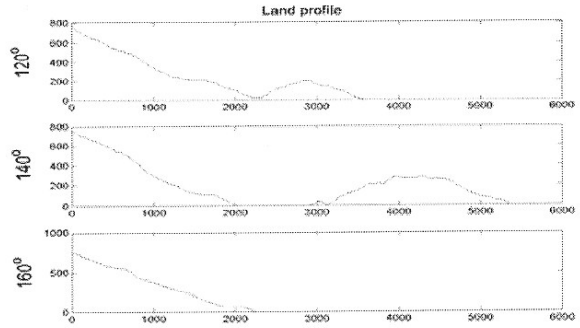


Fig.6 Directional terrain profiles

The measurements were taken at different distances along a radial traverse, 0km, 0.5km, 1km, 2km, 3km and 4km from the site as shown in Fig.6. Measurements were taken at heights equivalent to 40m, 80m, 120m, 160m and 200m above the local ground level at each location, which are typical heights for turbine operation. Measurements were also taken at heights equivalent to 300m, 400m and 750m to obtain more information concerning the wind characteristics and the gradient heights for each direction.

Important factors, such as changes of wind speed over the complex hilly terrain and the surface conditions need to be considered in order to accurately evaluate the wind characteristics for each direction. Further wind tunnel tests were conducted in which the upstream model was extended to include up to 7km from the main site. The detailed orography and terrain profiles for each direction are shown in Fig. 6.

$$T.M = \frac{\text{Wind speed at height, z, above the feature}}{\text{Wind speed at height, z, above the flat ground upwind}} \quad (4)$$

As a consistent approach wind was used for each directional test, topographical multipliers (*T.M*), as defined in Equation (4), were used to quantify the effects of the complex terrain on the mean wind speed. Not surprisingly, there was significant variation of the topographical multipliers between the directions and locations tested, which is consistent with other topographical studies of Hong Kong [6]. The topographical multipliers determined in the current wind tunnel study at the site location are shown in Table. 2.

	Group (NW) Topographical .Multiplier			Group (SE) Topographical .Multiplier		
Height(m)	340°	320°	300°	160°	140°	120°
40	1.576	1.627	1.519	1.563	1.519	1.586
80	1.415	1.491	1.440	1.519	1.431	1.484
120	1.292	1.380	1.348	1.421	1.316	1.409
160	1.246	1.375	1.352	1.384	1.307	1.372
200	1.232	1.345	1.314	1.349	1.285	1.356
300	1.209	1.283	1.277	1.293	1.258	1.283
400	1.253	1.283	1.283	1.286	1.272	1.272
750	1.206	1.206	1.203	1.218	1.211	1.213

Table 2: Topographical multiplier at YTS

Of the NW winds, those from 320° had consistently higher topographical multipliers. This is because there are fewer direct obstacles to the wind and because of the effects of a contraction on the windward mountain side, approximately 2.5km from the site, as shown in the terrain profile for 300° and 340° in Fig.6.

Of the SE winds, 160° has higher topographical multipliers, due to the open exposure to the sea. However, as shown in Fig.6, both 140° and 120° have small mountains upstream of the site that essentially decrease lower level wind speed as it proceeds towards the mountain.

Conclusions

- Based on the Weibull Distribution, between periods of 1997-2003, the hourly mean wind speed at Yi Tung Shan exceeded 4m/s for approximately 81% of the time.
- The prevailing non-typhoon wind directions at Yi Tung Shan are approximately north-north-west and south-south-east.
- The preliminary wind tunnel study results indicate that the topographical effects dominate the directional mean wind speeds at Yi Tung Shan.
- The detailed directional investigation indicated that wind from 320°(NW) had consistently higher topographical multipliers.
- A similar investigation will be conducted for another hilltop meteorological station, and also two offshore locations. Those results will be assessed and compared for suitability for use as wind power generation sites in Hong Kong.

Acknowledgements

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