CHARACTERISTICS OF MEAN WIND AND TURBULENCE PROFILES OF TYPHOON WIND

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ABSTRACT

Mean wind speed and turbulence are two main characteristics to describe conventional wind flow. Both these characteristics in an extreme wind event such as a typhoon is not well understood up to date. Hong Kong is a better place to investigate wind characteristics of typhoons as there are several typhoons pass through the country in every year. The Doppler SODARs and wind-profilers installed by Hong Kong Observatory are used to obtained measurements on both mean wind velocities and turbulence intensities up to 500 m height during two typhoons. The derived wind speed profiles are compared with widely used log-law and power-law wind profiles. The comparison showed that both the log-law and the power-law models successfully describe the vertical variation of mean wind velocities, especially for lower altitudes. The measured turbulence intensity profile is compared with both ESDU and AIJ turbulence profile models for non-typhoon wind. None of the ESDU or AIJ model could predict the real turbulence intensity profile accurately. The better prediction by AIJ model on the shape of vertical variation of the turbulence intensity indicates there is no appreciable difference in turbulence variation in typhoon boundary layer and conventional atmospheric boundary layer.

Keywords: Typhoon wind characteristics; mean wind profile; turbulence intensity profile; field observations

Introduction

Hong Kong is situated on the south east coast of Asian continent facing South China Sea, over which tropical cyclones frequently developed. Some of them intensified into typhoons and moved close to or across Hong Kong. On average, there are about 6 to 7 typhoons necessitate the issue of warning signals by the Hong Kong Observatory (HKO) in Hong Kong each year. As a result, Hong Kong is a convenient location for the study of tropical cyclone winds. Previous studies on tropical cyclone winds in Hong Kong were carried out by Choi (1978, 1983) and Hui & Larsen (2009).

Both meteorologists and wind engineers interest on mean wind speed and turbulence profiles in the typhoon boundary layer. Powell (1980) was one of the pioneers in determining mean wind profile within typhoon boundary over a sea surface by using low flying aircrafts and sea surface buoys. By using dropsonde data Powel et al (2003) reconstructed mean wind profile and showed that log law wind profile can be applied within lowest ~500m of typhoon boundary layer. This was later verified by Vickery, et al (2009) by using a large dropsonde data base. Tamura, et al (2007) and Pan, et al (2010) used relatively new techniques, Doppler SODAR and wind-profiler respectively, to measure wind characteristics of a typhoon boundary layer.
The limited measurement heights well below to cover entire typhoon boundary may not permit to use conventional methods to derive turbulence intensity profiles. Zhang, et al. (2009) and Yu, et al. (2008) derived the vertical profile of wind variances in the typhoon boundary layer over the sea by using low-level aircrafts and over the land by using portable observation masts respectively.

**Data and Post-processing**

The wind measurements were taken during the passages of typhoon Fengshen and Nuri by both the Doppler SODAR and the wind-profiler equipped in Siu Ho Wan (SHW) station (22°18′21″ Latitude and 113°58′45″ Longitude) in northern coast of Lantau Island (about 150m from the coast line) in Hong Kong. It can be considered wind flow under the open water exposure towards its NW-N-NNE and west directions and land in other direction E-SE-S-SW, with some tall mountains, e.g. the Lantau Peak (918m) to the southwest and the Tai Tung Shan (869m) to the south.

Both the Doppler SODAR and the wind-profiler are mounted at SHW station about 250m from the shore and at an elevation of 22m above mean sea level. The Doppler SODAR can measure 5-minute wind statistics, including the mean wind speed, the mean wind direction and the turbulent vertical wind ($w'$), up to 100 m at 5 m intervals. The lowest two measurements at the heights of 5m and 10m were discarded to eliminate influence of surrounding obstacles on lowest measurements. The wind-profiler can be operated in the “low-mode” or “high-mode” with the measurement heights ranging from 116m to 1500m at a 60m interval, and 260m to 6000m at a 200m interval respectively. The 10-minute wind statistics, including the mean wind speed, the mean wind direction and the turbulent kinetic energy dissipation rate ($\varepsilon$), were calculated based on the raw wind-profiler measurements.

Since the measurement height ranges for the Doppler SODAR and for the wind-profiler are distinctive, their data can be combined to yield the vertical profile of the wind statistics of interest. The calculated results were assembled to formulate the vertical profile of the wind statistics up to 500m, which is the gradient height according to Code of practice on wind effects in Hong Kong (Committee on Review of the Code of Practice on Wind Effects, 2004). Afterwards, the formulated vertical profiles of mean wind speeds were fitted to both the log-law and the power-law by using, the Levenberg-Marquardt algorithm (Levenberg, 1944). As for the configuration of the Levenberg-Marquardt algorithm, the number of the maximum iterations allowed was 10000 and the desired relative error was $1.48 \times 10^{-8}$. In calculating the fitted results presented in this study, the desired relative error was always achieved before reaching the maximum allowed iterations. In order to eliminate the influence of thermal effects, measured data of MBL wind speed higher than 10m/s are selected for data analysis. The allowable average MBL wind direction deviation is limited to 45° to avoid influence of nearby topography features. It is also discarded data with ambiguous wind directions.

The vertical profiles of the turbulent vertical wind ($w'$) (up to 100m), and of the turbulent kinetic energy dissipation rate $\varepsilon$ (in the range of 100m ~ 500m) were derived using the Doppler SODAR measurements and wind-profiler measurements respectively. Though Doppler SODAR is capable of measuring turbulent wind in all three spatial directions, the turbulent vertical wind is, however, considered more reliable when compared with the horizontal turbulent winds since one of the antennas pointing to the zenith to measure vertical winds directly. The estimated turbulence intensity profiles are then compared to the model given by both the Japanese Code (AIJ, 2004) and ESDU (1993).
The vertical profile of vertical turbulence intensity can be transferred to longitudinal turbulence intensity \((u' / u)\) as proposed by Solari (2001)

\[
\begin{align*}
u' &= \rho w' \\
&= \frac{\rho}{\lambda} \left( \frac{2}{3} \right)^{2/3}
\end{align*}
\]

In Equation (1), \(w'\) is vertical turbulent and \(\rho\) is the longitudinal turbulence ratio taken as 2.5.

Above 100 m height level, the turbulence kinetic energy dissipation rate is first combined with a turbulent length scale model to derive the turbulent kinetic energy as recommended by (Launder & Spalding, 1974; Detering & Etling, 1985)

\[
k = \left( \frac{l}{C_\varepsilon} \right)^{2/3}
\]

Where, \(k\) is the turbulent kinetic energy and \(l\) is the turbulent length scale, \(\varepsilon\) is the turbulent kinetic energy dissipation rate and \(C_\varepsilon\) is the model constant in \(k\)-\(\varepsilon\) model closure equals to 0.09. Then, the turbulence intensity is derived by using calculated turbulent kinetic energy and longitudinal turbulent wind as

\[
u' = \rho_k \sqrt{k}
\]

Where, \(u'\) is the longitudinal turbulent wind, \(k\) is the turbulent kinetic energy and the ratio \(\rho_k\) is taken as 0.955. The turbulent length scale is calculated according to recommendations of Blackadar (1962)

\[
l = \frac{Kz}{1 + \frac{Kz}{\eta}}
\]

in Equation (4), \(l\) is the turbulent length scale, \(K\) is the von Karman constant (i.e. 0.4), \(z\) is the height in meters and \(\eta\) is the ultimate length scale in the upper atmosphere. \(\eta\) can be calculated according to the surface roughness parameters as,

\[
\eta = k_b u_* f
\]

Where \(k_b = 63 \times 10^4\) (Pena, et al., 2009), \(u_*\) is the surface shear velocity and \(f\) is the Coriolis parameter. This model validity in near neutral conditions is conserved in this study by selecting wind speed higher than 10 m/s for analysis.

Two typhoons Fengshen and Nuri, passed through Hong Kong in 2008 were selected as case studies. The typhoon Fengshen is classified as a sever tropical storm which was landfall in Hong Kong On 24th of June 2008. Before it made landfall at Kuichong, Shenzen in early morning on 25 June, it hit east part of Hong Kong. Typhoon Nuri is also a severe tropical storm which sustained speed of 17.5-32.5 m/s and the gust of 50 m/s. Typhoon Nuri entered to eastern part of Hong Kong in evening on 22nd of August. Weakened Nuri reorganized itself passed over Victoria Harbour from east to west before went through Lantau Island to enter south China coast. The center of Typhoon Nuri is much closed to SHW station, which made it good for investigating the wind characteristics in the typhoon boundary layer.
Results

Figure 1 presents the mean wind profiles of Fengshen and the fitted results. The comparison between the observed and the fitted mean wind profile indicates that both the log-law and the power-law models describe the mean wind profile in the typhoon boundary layer with satisfactory accuracy. Another important observation of four wind speed profiles is the effects of inland topography. Except the wind profile with time stamp 03.13 to 04.14 on 2008-6-25, the profile over the sea fetch, other profiles relate to wind flow over inland. Wind flow over sea fetch has relatively flat profile over 150m height, which implies a lower gradient height (~150 m) when compared to the profiles from the inland directions. The surface roughness parameters derived in the mean wind profile fitting. Figure 2 shows the turbulence intensity profiles, derived based on the observed turbulent vertical wind (below 100m) and the turbulent kinetic energy dissipation rate (above 100m), and the model profiles calculated according to the ESDU model and AIJ models. Between two models, AIJ model predicts vertical variation of the turbulence intensity accurately compared to ESDU model.

![Fig. 1: the mean wind profiles of Typhoon Fengshen (2008) and their fitted results. The time periods are indicated by the subfigure titles.](image)

The vertical profiles of observed wind speed during typhoon Nuri with two empirical models are shown in Figure 3. All four wind profiles are resulting from wind flow over sea fetch. As expected measured wind profile is tally with other two empirical wind profile in height lower than 100 m. However, deviations above 100m height indicate that occurrence of different gradient heights as a result of the large-scale typhoon meteorology instead of influence of surface roughness. Figure 4 presents the vertical profiles of the turbulence intensity of calculated, and ESDU and AIJ models. At lower altitudes, calculated turbulence profiles have lower turbulence intensity compared to ESDU and AIJ profiles models. However, contrary to conventional turbulence intensity profile, which decays with increase of height, measured
turbulence profile has higher values at high altitude levels. This may be resulted from a combined effect of fluctuation of mean wind speeds and localized turbulence effect.

![Graphs showing turbulence intensity profiles](image1)

**Fig. 2:** The turbulence intensity profiles of Typhoon Fengshen (2008) and the model predicted profiles. The time periods are indicated by the subfigure titles.

![Graphs showing mean wind profiles](image2)

**Fig. 3:** The mean wind profiles of Typhoon Nuri (2008) and their fitted results. The time periods are indicated by the subfigure titles.
Fig. 4: The turbulence intensity profiles of Typhoon Nuri (2008) and the model predicted profiles.

**Discussion**

By comparison of mean wind profiles, both the log-law and the power-law models describe the vertical variation of mean wind speed in lower portion of the typhoon boundary layer with a satisfactory accuracy, especially for the profile below height 100m. However, further investigation is required as inland topography may strongly affect the shape of the profile and caused wind speed profile deviates from its conventional shape as predicted by empirical models. The surface roughness parameters can be expressed via power law exponent ($\alpha$) or surface roughness length ($z_0$) by fitting measured data to power-law and log-law wind profiles respectively. Table 1 presents the derived surface roughness parameters in term of surface roughness $z_0$ and power law exponent $\alpha$ for each time stamps of typhoons Fengshen and Nuri.

Table 1 the aerodynamic roughness length fitting results

<table>
<thead>
<tr>
<th>Typhoon name</th>
<th>Surface roughness ($z_0$)</th>
<th>Power law exponent $\alpha$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Fengshen</td>
<td>0.4472</td>
<td>1.3186</td>
</tr>
<tr>
<td>Nuri</td>
<td>0.6618</td>
<td>0.0314</td>
</tr>
</tbody>
</table>

The derived surface roughness parameters are larger than the expected value at SHW under corresponding conditions. Choi (1978) suggested this might be due to the large sea waves created by strong typhoon wind. However, same trend found in other direction indicates that, higher surface roughness parameter is a characteristic of typhoon boundary layer. Because typhoon is an extreme weather condition, turbulence mixing with the typhoon boundary layer...
is higher than that induced by surface roughness elements (Powell, et al., 2003; Wang and Wu (2004); Zhang, et al., 2009). Since at lower altitudes log-law profile directly relate to the turbulent shear stress, profile may deviate from its original shape determined only by surface roughness and get a similar shape corresponding to higher roughness value.

In conventional meteorology point of view, atmospheric boundary layer height is determined by surface drag such as boundary layer grows with increase of surface drag. This condition can be found from Figure 1 for wind flow over sea fetch and inland separately. However, data of typhoon Nuri indicate that, even within a sea fetch boundary layer could have different heights according to the location of the center of typhoon. This is an important factor because typhoon boundary layer height is a function of radial pressure distribution and gradient wind (Kepert, 2001).

The main difference between calculated turbulence intensity profile and two models is the lesser turbulence intensity values at lower altitudes. One possible reason for this discrepancy is anisotropy of turbulence in typhoon boundary layer is higher than in the conventional boundary layer (Solari, 2001). Thus, longitudinal turbulence in typhoon boundary layer might be smaller than in normal conditions. The second possible explanation is higher turbulence stresses results within a typhoon boundary layer cannot predict by models based only on surface roughness parameter. In addition to that, it is not necessary to have higher longitudinal turbulence stress within a strong turbulence condition. This means that larger turbulence could be resulted from higher vertical turbulence component rather than from dominating longitudinal component of a typhoon boundary layer. Though there is a difference in magnitude of turbulence intensity, AIJ model predicts similar vertical variation as calculated turbulence intensity profile based on measurements. This means that turbulence intensity within a typhoon boundary layer has the same variation in height as one observed in non-typhoon boundary layer.

**Conclusion**

The mean wind and turbulence characteristics of typhoons Fengshen and Nuri were measured by using a Doppler SODAR and a wind profiler equipped at SHW station, Hong Kong. The vertical profile of mean wind and turbulence profiles were derived by using measured data. The mean profiles were then fitted to both the log-law and power-law and revealed better agreement at lower altitudes. The calculated surface roughness from fitted profile is larger than value corresponding to the condition of SHW station. This might be caused by larger sea waves induced by strong wind and/or as a characteristic of typhoon boundary layer. Derived turbulence intensity profile compared with the ESDU and AIJ models found that none of the models can predict the turbulence level accurately. This may be due to either higher anisotropy nature of turbulence within typhoon boundary layer may lower longitudinal turbulence level or higher turbulent shear stresses of the typhoon wind cannot capture from models based only on surface roughness parameter. However, the shape of the AIJ model is similar to the shape of derived turbulence profile indicates that the turbulence models designed for the non-typhoon boundary layer can be still applicable to typhoon boundary layer.

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