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Roughness lengths and turbulence intensities for wind over water

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Abstract

Analysis of recent gust factor data obtained by the Australian Bureau of Meteorology from automatic weather stations located offshore, represented by the Fawkner Beacon in Port Philip Bay, Victoria, and several offshore reefs in ocean locations affected by Tropical Cyclone 'Yasi', is presented. This indicates that the well-known Charnock [1] model of roughness lengths for over water winds represents the variations with mean wind speed quite well. However, the inferred turbulence intensities are lower than those currently given in codes and standards for over-water winds.

Introduction

There is a clear tendency, throughout the world, for population to migrate to coastal towns and cities. Also many oil and gas facilities and windfarms are located offshore. This results in many structures being exposed to severe over-water winds generated by synoptic storms, such as gales and tropical cyclones. While there have been quite a few studies of wind over water, these have often been driven by phenomena at lower wind speeds, such as evaporation and wave generation, rather than wind forces on structures.

This paper discusses turbulence intensities and roughness lengths for wind over a semi-enclosed bay, and the open ocean, making use of gust factors from automatic weather stations.

Bureau of Meteorology data

The Bureau of Meteorology (BoM) records automatic weather station (AWS) data on wind speeds and direction every half hour from about 700 stations across Australia. Amongst these is a station in Port Phillip Bay, Victoria, known as the 'Fawkner Beacon'. This station is at the north end of the Bay, approximately 5 kilometres from Brighton to the east, and about the same distance from Williamstown to the NNW, (Figure 1). Data recorded from this station during 2013-17 is discussed here.

There are also AWSs located on two offshore reefs, and on Willis Island, in the Coral Sea off the coast of North Queensland. These recorded during the approach of Tropical Cyclone 'Yasi' in February 2011, and some of these data have also been analysed, and results are presented here.

The wind speeds recorded by the BoM, and published on the internet shortly after their recording, are 10-minute averages, and maximum 3-second gusts during that 10-minute period. The ratio of these two values, gives gust factors which can provide useful information on the turbulence intensity, and hence the effective roughness length and terrain category, by direction sector.

Figure 1. Satellite views of Port Phillip Bay showing automatic weather stations operated in the Melbourne area by the Bureau of Meteorology, with the Fawkner Beacon AWS ringed in red in the upper view.

Analysis Procedure

For the samples of gust factors (i.e. max 3-second gust/ 10-minute mean) obtained, the following procedure was used to derive turbulence intensity and roughness length:

- For each sample with known mean wind speed, a theoretical 'expected' peak factor, γ_u, was calculated using the approach described by Holmes *et al*. [2], based on random processes, and assuming the von Karman spectral density given in the Australia/New Zealand Standard for Wind Actions AS/NZS 1170.2 [3] with an integral length scale of 85m.

- A turbulence intensity was then calculated for each sample from equation (1):

$$I_u = \frac{G-1}{\gamma_u} \tag{1}$$

where G is the recorded gust factor for that sample.

- The resulting turbulence intensities were then averaged over all the samples available for each station-direction set.

- Equation (2) is a well-known empirical equation for turbulence intensity in the strong-wind surface layer, and can be used to get an estimate of aerodynamic roughness length, z_0, from the turbulence intensity:

$$I_u(z) = \frac{1}{\log_e(z/z_0)} \tag{2}$$

That is for z equal to 10 metres, and inverting equation (2):

$$z_0 \cong 10.\exp\left(\frac{-1}{I_u}\right) \tag{3}$$

Although there are a number of assumptions made in the above procedure, these are consistent with accepted models of strong synoptic-scale winds used in wind engineering, and related fields.

The Charnock formula

Charnock [1] applied dimensional analysis to wind profile measurements of wind flow over water, which closely fitted the logarithmic law, and proposed the following expression for the roughness length, z_0:

$$z_0 = \frac{a u_*^2}{g} \tag{4}$$

where u_* is the friction velocity, g is the gravitational constant, and a is a 'constant', sometimes known as 'Charnock's constant'.

Applying the logarithmic law, u_* can be written:

$$u_* = \frac{k.\bar{u}_r}{log_e(z_r/z_0)} \tag{5}$$

where k is von Karman's constant ($\cong$ 0.4), and $\bar{u}_r$ is the mean velocity at a reference height z_r.

Then substituting in (4),

$$z_0 = \frac{a}{g}.\left[\frac{k.\bar{u}_r}{log_e(z_r/z_0)}\right]^2 \tag{6}$$

Equation (6) is an implicit equation for z_0 that can be solved by iteration.

Measurements from Fawkner Beacon

A total of 907 values of gust factors from Fawkner Beacon in Port Phillip Bay were obtained between 2013 and 2017, spanning the full range of wind directions. The largest data set (280 values) was collected for the north direction – this is known to be the most common direction for strong winds in Melbourne. However, very little data was obtained from NE and ENE - these directions are generally not the source of strong winds in the Melbourne area. 10-min mean wind speeds ranged from 9 to 45 knots (4.6 to 23.1 m/s)

Figure 2 shows the calculated turbulence intensities, using equation (1), for all directions except NE and ENE for which there were insufficient data collected.

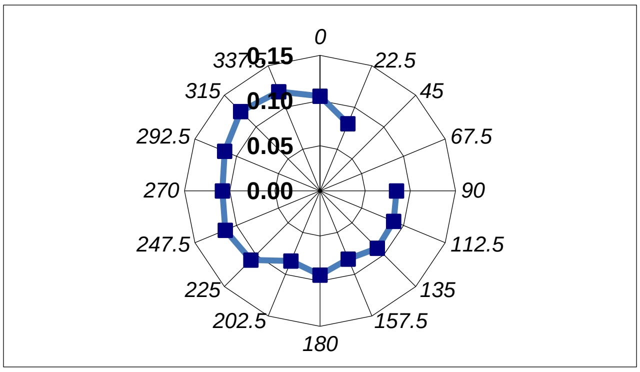

Figure 2. Turbulence intensity at the Fawkner Beacon (17m above MSL)

The turbulence intensity averaged over all directions is about 0.10, with slightly higher values for the north-west, and lower values for wind from the south and east. For over-water winds (i.e. 'Terrain Category 1'), AS/NZS 1170.2 [3] gives a value of turbulence intensity at 17 metres height of 0.15 – i.e. about 50% higher than the average shown in Figure 2.

It is not clear why generally higher turbulence intensities occur for northwest winds than for easterlies, as the station is nearly equidistant from land for both those directions (see Figure 1).

Further processing was carried out on the 280 values obtained for northerly winds. The data was segregated into 8 groups each with similar 10-minute wind speeds, with an average number of 35 in a group. The turbulence intensity was calculated from the gust factor for each sample using equation (1), and the roughness length for that speed range estimated using equation (3). Then averages were calculated for each group.

Figure 3 shows the average values of roughness length plotted against the average 10-minute mean wind speed for the group. Also shown is the Charnock expression for z_0, (i.e. equation (4) or (6)) with the 'constant' a taken as 0.04.

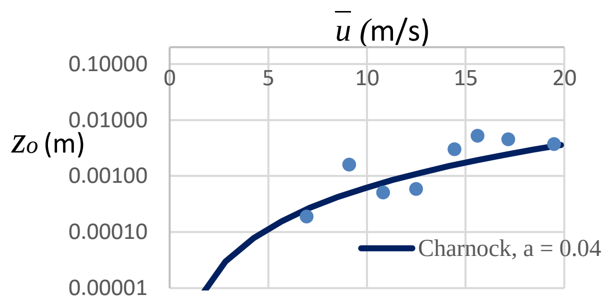

Figure 3. Roughness length versus mean wind speed for northerly winds at Fawkner Beacon

Figure 3 shows that the roughness length increases with mean wind speed, as predicted by the Charnock formula. For this data the value of the constant, a, of about 0.04 is somewhat greater than values previously found.

Measurements from offshore stations in Cyclone 'Yasi'

Tropical Cyclone 'Yasi' was a severe storm that crossed the coastline of North Queensland, near Tully, on 3rd February 2011 [4]. A wind field analysis for the cyclone [5] included assessment of recorded wind speeds from Flinders Reef, Holmes Reef and Willis Island in the Coral Sea, during the approach of the storm on

February 2nd and 3rd. The track of the storm and the location of the AWS in the Coral Sea are shown in Figure 4. These data provided a unique opportunity to assess gust factors, turbulence intensities and surface roughness for wind over water, at close to design level wind speeds.

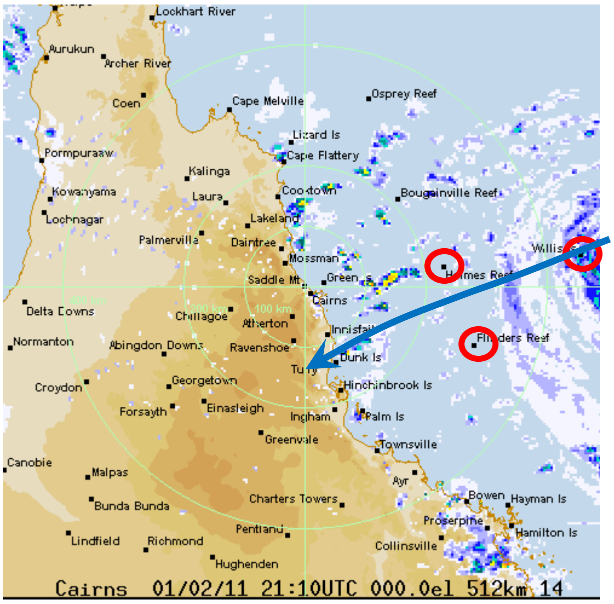

Figure 4. Track of Tropical Cyclone 'Yasi' on February 2-3, 2011, showing the automatic weather stations in the Coral Sea ringed in red (*map sourced from the Bureau of Meteorology web site*).

For the present paper, gust factors averaged over five wind-speed ranges from Holmes Reef and two from Flinders Reef were processed to determine turbulence intensities and roughness lengths. The number of ten-minute periods averaged for each data point varied between four and thirty-three.

Several values from Willis Island are also included. Willis Island was crossed by the 'eye' of the cyclone, although unfortunately the anemometer failed soon after the readings were recorded.

Table 1 summarises the twelve values of averaged mean wind speeds, gust factors, turbulence intensities and roughness lengths. The latter were derived using equations (1) and (3) respectively. The range of 10-minute mean wind speeds is 15 to 38 m/s.

It is notable that the values of turbulence intensity in Table 1 are all lower than those given in *Table 6.1* of AS/NZS 1170.2 [3] for 10-metre height, for over-water winds (i.e. Terrain Categories 1 or 1.5)

Figure 5 shows a plot of the calculated values of roughness length, versus mean wind speed, together with the Charnock formula with the parameter, *a*, equal to 0.01. The Coral Sea data show reasonable consistency with the Charnock relationship, although with a lower value of the 'constant', *a*, than for the Port Phillip Bay data.

Discussion

The roughness length estimates, for moderate (Figure 3) to strong (Figure 5) winds over water, is adding to the increasing body of evidence for lower values of z_0 than those that had been previously assumed at design wind speeds. The previously-assumed higher values had originated from extrapolating measurements at lower mean wind speeds. However, the important paper by Powell *et al.* [6] demonstrated that roughness lengths over the open Atlantic Ocean remained in the 1-3 mm range even in the highest winds speeds near the centre of hurricanes.

Station (no of averages)	Gust factor	Mean wind speed (m/s)	Turbulence intensity	Roughness length (m)
Holmes reef (6)	1.227	15.5	0.096	0.00030
Holmes reef (19)	1.289	18.5	0.122	0.00278
Holmes reef (16)	1.231	23.7	0.098	0.00039
Holmes reef (33)	1.266	28.7	0.114	0.00160
Holmes reef (14)	1.259	33.7	0.113	0.00145
Flinders reef (7)	1.251	19.6	0.106	0.00080
Flinders reef (4)	1.254	22.8	0.108	0.00096
Willis Island (12)	1.261	18.9	0.110	0.00114
Willis Island (6)	1.261	24.3	0.111	0.00124
Willis Island (10)	1.340	28.4	0.146	0.01071
Willis Island (5)	1.316	34.2	0.138	0.00716
Willis Island (4)	1.307	37.7	0.136	0.00624

Table 1. Averaged wind speed data from offshore stations during Cyclone 'Yasi', 2 February 2011

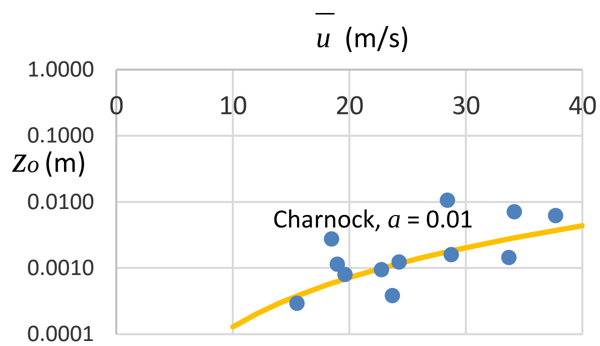

Figure 5. Roughness length versus mean wind speed for winds over the Coral Sea during the approach of Tropical Cyclone 'Yasi', 2/3-Feb-2011

Several codes and standards, including AS/NZS 1170.2:2011 [3] (with Amendment 2, 2012) have now reduced their roughness lengths (or equivalent power law exponents) for over-water winds. However, there are still some codes or standards for which this has not occurred – an example is ISO 19901-1 [7], a document widely used for offshore structures in the oil and gas industries.

The turbulence intensities shown in Figure 2 (and values derived from the Cyclone 'Yasi' measurements in Table 1) suggest that *Table 6.1* in AS/NZS 1170.2 [3] for Terrain Category 1 overestimates the correct values for turbulence intensity over-water winds. This may be significant for dynamically-sensitive structures, and should be addressed.

The measurements from Fawkner Beacon and Tropical Cyclone 'Yasi' both showed reasonable agreement with the Charnock model of roughness length versus mean wind speed (equations (4) and (6). However, the values of the so-called 'constant', a, differed considerably, with 0.04 indicated for the winds over Port Phillip Bay and 0.01 for the Coral Sea. A similar value to the latter one, for mean wind speeds up to 40 m/s, was indicated by the dropsonde data reported by Powell *et al*. [6] for the Atlantic Ocean. The variability of the Charnock parameter, a, suggests that another variable, such as water depth, may be involved.

Conclusions

This paper has presented information on turbulence intensities and roughness lengths for moderate to strong winds, based on recorded data from automatic weather stations in Port Phillip Bay, Victoria, and the Coral Sea off the Queensland coast. The relatively low values of inferred roughness lengths support the conclusions of Powell *et al.* [6], and justify the lower terrain categories for over-water winds included in the 2012 amendment to Australian/ New Zealand Wind Actions Standard. However, the low values of observed turbulence intensities suggest that values of this parameter for over-water winds in AS/NZS 1170.2 are too high.

References

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