WIND TURBULENCE OVER SEAS IN TROPICAL CYCLONES

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ABSTRACT

A study of wind data collected from the Waglan Island anemometer (Hong Kong) during 39 tropical cyclones indicates that turbulence intensity values in excess of 20% at a reference height of 50 m are likely during extreme wind conditions in a tropical cyclone. The implied surface drag coefficient of approximately 0.01 in these extreme wind conditions is consistent with wind flow over a land surface roughness of trees and suburban housing, but is much higher (by a factor of five) than that predicted by the currently accepted formulae from the reviews of Garratt and Wu for wind flow over a fully developed sea in neutral atmospheric conditions. For wind loading design calculations in extreme wind in tropical cyclone conditions it is recommended that mean wind and turbulence intensity profiles should be calculated with a roughness length z_0 = 0.20 m in the Deaves and Harris wind model.

1 INTRODUCTION

Major structures planned and being built in ocean environments are becoming increasingly wind sensitive as the frequency of their first mode becomes lower. The response of such structures to wind action is not only a function of wind speed but is significantly dependent on the turbulence structure of the wind flow, more explicitly on the turbulence intensity and spectral distribution. Similarly, wind loading on harbour and onshore structures are dependent on these same characteristics. It is important therefore to have estimates of the turbulence characteristics of wind flow over the sea surface in extreme wind conditions, such as might occur for return periods of 20 to 2000 years to cover limit state serviceability and collapse conditions.

Wind data collected in Hong Kong at several anemometer sites for 123 tropical cyclones causing persistent gales since 1884 have been corrected recently for anemometer position error and used to estimate design wind speeds for this area. In particular, model tests to correct wind data collected at a height of 75 m above sea level on Waglan Island, in a full ocean exposure, have given some access to wind turbulence data over the sea in tropical cyclone, extreme wind conditions. These results will be presented to provide some full scale information about wind structure over the sea in extreme wind conditions.

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2 WIND MODELS OVER SEA AND LAND

2.1 Over Land

The most recent review of data compiled to derive a wind model over land is that by Deaves and Harris (1978). The Deaves and Harris model of the structure of strong winds is a most thoroughly researched model and is in wide use in the wind engineering field. It is based on classic logarithmic law mean wind speed profiles and defines surface roughness in terms of the roughness length, z_o.

i.e. $$\frac{\bar{V}_z}{u_*} = \frac{1}{\kappa} \ln\left(\frac{z}{z_o}\right) \qquad (1)$$

where u_* is the friction velocity $\left(= \sqrt{\frac{\tau}{\rho}} \right)$

$\bar{V}_z$ is the mean wind speed at height z

z is height above ground level

z_o is a roughness length

κ is the von Karman constant (=0.4)

ρ is air density

τ is surface wind shear stress

For the purposes of this study the central parameter is turbulence intensity, I_z, defined as,

$$I_z = \sigma_{v_z} / \bar{V}_z \qquad (2)$$

where σ_{v_z} is the standard deviation of wind speed at height z

A summary of the equations used in the Deaves and Haris wind model are given in Appendix 1. A study has been carried out (Melbourne 1980) using the Deaves and Harris wind model with a 50 ms^{-1} mean gradient wind speed (appropriate to strong wind, design conditions) and varying z_o, until a best fit with profiles for four defined surface roughness categories was obtained. A summary of the relevant turbulence intensity characteristics and roughness length values, with a little rounding, for four surface terrain roughness conditions is given in Table 1.

TABLE 1

TURBULENCE INTENSITY CHARACTERISTICS FOR THE DEAVES AND HARRIS MODEL OVER FOUR SURFACE TERRAIN ROUGHNESS CONDITIONS

Terrain Roughness	Height (m)	Turbulence Intensity I_z
1. Flat desert, snow, (z_o = 0.002 m) ($C_{D_{10}}$ = 0.0022)	5 10 50 100 200	0.165 0.157 0.128 0.108 0.085
2. Level grass plains, isolated trees, airfields (z_o = 0.02 m) ($C_{D_{10}}$ = 0.0041)	5 10 50 100 200	0.196 0.183 0.151 0.131 0.107
3. Trees, suburban housing (z_o = 0.2 m) ($C_{D_{10}}$ = 0.0104)	5 10 50 100 200	- 0.239 0.188 0.166 0.139
4. Forests, hilly terrain, city centres (z_o = 2.0 m) ($C_{D_{10}}$ = 0.061)	5 10 50 100 200	- 0.448 0.270 0.233 0.196

2.2 Over Sea

In spite of a bounteous literature, until very recently it has been a matter of contention whether the drag coefficient of the wind over the sea assumes a constant value for strong winds. The experimental difficulties probably account in large measure for this imprecision, but it will come as no surprise to find that measurements of strong wind parameters over the sea are very sparse, still less that adequate mathematical representations are wanting.

Garratt (1977) in his review of drag coefficients over oceans and continents concluded, that "observations are consistent with Charnock's (1955) relation,

$$z_o = \frac{\alpha\, u_*^2}{g} \tag{3}$$

where α is a constant" (later to be given a value of 0.0185) and that "for $4 < \bar{V}_{10} < 21\ ms^{-1}$ a neutral drag coeffficient (referred to 10 m) could be given by

$$C_{DN_{10}} \times 10^3 = 0.51\ V_{10}^{0.46}$$

or

$$C_{DN_{10}} \times 10^3 = 0.75 + 0.067\ V_{10} \tag{4}$$

which is similar to that proposed by Deacon and Webb (1962) and Wu (1969) for wind speeds less than 15 ms^{-1}, and that observations did not support a constant C_{DN} above 15 ms^{-1} as deduced by Wu (1969)" (p926).

Wu (1980) revisited the field and with more data further confirmed the relevance of Charnock's relation and suggested that the most appropriate value for the constant, α, was 0.0185 with $\kappa = 0.40$, and that

$$C_{10} = (0.8 + 0.065\ V_{10}) \times 10^{-3} \tag{5}$$

which he also showed (Wu, 1983) is in close agreement for a reference height of 10 m to the generalised expression obtained from (1) and (3), i.e.

$$C_{D_z} = \frac{\tau}{\rho \bar{V}_z^2} = \left[\frac{u_*}{\bar{V}_z}\right]^2$$

$$= \left[\frac{\kappa}{\ell n(1/a\ C_{D_z} F^2)}\right]^2 \tag{6}$$

where F is a form of Froude number

$$\left(F = \bar{V}_z/\sqrt{g\ z}\right)$$

Wu (1983) also suggested on the basis of some new data that Charnock's relation and equation (5) appear to be applicable to much higher wind speeds than previously thought, even in hurricanes.

The conclusions of this recent work, in respect of values of drag coefficient and roughness length for wind flow over the sea surface as function of wind speed are summarised in Table 2. Values of the roughness length of the order 0.010 m, commensurate with a mean wind speed of 40 ms^{-1} at 10 m over the sea from Table 2, bear no relation to the physical scales apparent in a fully aroused sea. Of course, a reference height of 10 m is an obvious nonsense at such wind speeds when wave heights in excess of 20 m are likely to be present. It is not surprising that the applicability of current formulae for wind flow over land and sea is being challenged in respect of extreme (design) wind storm events over the sea.

TABLE 2

EVALUATION OF SURFACE DRAG COEFFICIENT, ROUGHNESS LENGTH AND FRICTION VELOCITY FROM EQUATIONS 5, 3 AND 6 RESPECTIVELY.

$\bar{V}_{10}$ ms^{-1}	$C_{D_{10}}$ X 10^3	z_o m	u_* ms^{-1}
10	1.45	0.0003	0.15
20	2.10	0.0016	0.84
30	2.75	0.0047	2.48
40	3.40	0.0103	5.44
50	4.05	0.0191	10.13

3 FULL SCALE MEASUREMENTS FROM WAGLAN ISLAND

The initial analysis of the Waglan Island data was based on the highest mean and three-second maximum gust wind speeds recorded by Dines anemometers for each tropical cyclone causing persistent gales in the Hong Kong region. These data were corrected for anemometer position error from wind tunnel topographical model studies of the anemometer sites. During the analysis of this data it was realised that the anemometer on Waglan Island, which is a small rock outcrop SE of Hong Kong Island, was ideally sited for the purpose of obtaining wind data over the sea in extreme wind conditions, because it is completely exposed to the open ocean for wind directions NE to SW and for the remainder the ocean fetch is mostly 5 km or more. The anemometer at Waglan Island is on a mast, approximately 20 m above ground level and 75 m above mean sea level. The anemometer position errors were initially measured to give freestream conditions at a reference height of 10 m. For extreme wind conditions and attendant wave heights this is obviously quite an artificial reference. Subsequent wind tunnel measurements have been made to correct these anemometer readings to the height of the freestream streamline passing through the anemometer.

3.1 Anemometer Position Error Corrections

A 1/600 scale model of Waglan Island, shown in Figure 1, was tested in two turbulent boundary layer wind models. The wind models were generated in a 2 x 2 x 15 m working section using triangular vorticity generators at the front followed by surface roughness blocks. The two wind models had the scaled characteristics of wind flow over open terrain and suburban/treed terrain, i.e. $z_o \approx 0.02$ and 0.2 respectively or in terms of power law profiles, for exponents $\alpha = 0.15$ and 0.24, where $\left(\bar{V}_z = \bar{V}_g (z/\bar{V}_g)^{\alpha} \right)$. The ratios of the parameters, mean and gust wind speed at the anemometer position and at a scaled height of 50 m in the freestream flow, was measured using hot wire anemometry. In fact, there have been four anemometer positions on Waglan Island since 1952. Between 1952 and 1963 the anemometer was placed on the Observatory Building with good exposure. From 1964 to July 1966 the anemometer was located 3 m above the Signal Tower roof, and being in

FIG. 1 1/600 scale wind tunnel model of Waglan Island used to determine anemometer position error corrections.

the wake of the building, these wind records are useless. In July 1966 the anemometer was raised to 19.5 m above ground level and was then shifted slightly again in December 1971 to its current position. An example of the position error corrections for mean wind speed, $\bar{V}$, and maximum gust wind speed, $\hat{V}$, are given in Figure 2 for the current anemometer position. Since these measurements were made, a set of mean velocity anemometer corrections was measured at the University of Western Ontario, Surry et al. 1981, for all anemometer positions and which compare well with the corrections shown in Figure 2.

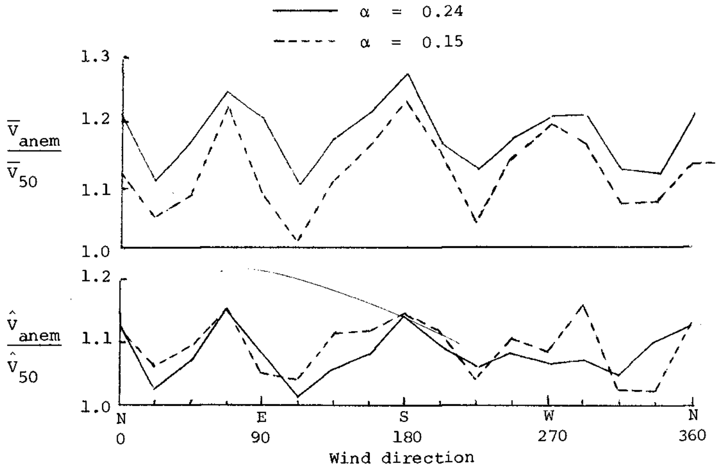

FIG. 2 Mean and gust wind speeds at the Waglan Island anemometer position (1971-) relative to freestream at 50 m above MSL as a function of wind direction for two surface roughness conditions (i.e. two boundary layer profiles)

Apart from the fact that a 10 m freestream reference height is physically meaningless there was another very important reason for correcting anemometer records to a greater height in the freestream flow: the sensitivity of the position error corrections to variations in the approach profile increases with reduction of the freestream reference height. It was therefore decided to use a reference height approximately the same as the freestream height of the streamline which passes through the anemometer on top of the buildings on the island (75 m). Accordingly a freestream reference height of 50 m above MSL was chosen. As can be seen in Figure 2 the correction ratios for the two approach profiles are almost the same for mean and gust wind speeds. The maximum mean and gust wind speeds from the Waglan Island anemometer for each tropical cyclone causing persistent gales in Hong Kong since 1982 (excluding records from January 1964 to June 1966), corrected to refer to a height of 50m above MSL in freestream flow, are given in Table 3.

3.2 Turbulence Intensity Measurements

In Table 3 values of the peak gust over mean wind speed ratio have been calculated. There have been a number of formulae offered in the literature which relate turbulence intensity to the ratio of the maximum gust over mean wind speed, most of which effectively state the number of standard deviations above the mean one might expect the maximum value to occur on average for a given short averaging period. This relationship depends on the response time of the anemometer as well as the averaging period. Deaves and Harris in reviewing

TABLE 3

MAXIMUM MEAN AND GUST WIND SPEEDS MEASURED AT WAGLAN ISLAND DURING TROPICAL CYCLONES CAUSING PERSISTENT GALES AT HONG KONG, CORRECTED TO REFER TO FREESTREAM CONDITIONS 50 m ABOVE MEAN SEA LEVEL

	Uncorrected anemometer data				Corrected to reference to 50 m above MSL in freestream approach flow			
	Max mean hourly wind speed		Max. gust wind speed					
	Direct.	$\bar{V}$ ms^{-1}	Direct.	$\hat{V}$ ms^{-1}	$\bar{V}$ ms^{-1}	$\hat{V}$ ms^{-1}	$\hat{V}/\bar{V}$	$\sigma_v/\bar{V}$
1953 Sept 18	NNE	30.9	ENE	47.9	28.6	41.7	1.46	0.12
1954 Aug 29	ENE	25.7	ENE	48.4	24.0	42.1	1.75	0.20
Nov 6	E	31.4	E	48.4	27.3	45.7	1.67	0.18
1957 July 16	S	22.6	S	36.5	19.7	32.0	1.62	0.17
Sept 22	E	31.4	ENE	51.5	27.3	44.8	1.64	0.17
1960 June 9	SSW	30.9	SSW	54.1	26.9	49.2	1.83	0.22
1961 May 19	ESE	25.2	SW	35.5	22.9	33.8	1.48	0.13
Sept 10	W	22.1	W	33.5	19.1	30.7	1.61	0.16
1962 Sept 1	NW	41.2	NNW	60.2	37.1	57.3	1.54	0.15
1966 July 13	ENE	25.7	E	36.5	22.4	34.4	1.54	0.14
1967 Aug 21	ENE	22.6	ENE	31.9	19.7	27.7	1.41	0.11
Oct 18	E	24.2	E	32.4	21.6	30.6	1.42	0.11
Nov 7	E	20.6	E	26.8	18.7	25.3	1.35	0.10
1968 Aug 21	NNE	34.5	NE	58.2	31.5	54.4	1.73	0.20
Sept 3	ENE	20.1	ENE	25.7	17.5	22.4	1.20	0.08
1969 July 28	SW	27.8	SW	38.1	25.3	36.3	1.43	0.12
1970 July 16	S	31.9	SW	42.7	25.7	40.7	1.58	0.16
Aug 2	SW	20.6	SW	30.4	19.6	29.0	1.48	0.13
Sept 14	NW	20.6	NW	28.3	19.3	27.5	1.42	0.11
1971 June 18	SSE	26.8	E	35.5	22.9	33.5	1.46	0.13
July 22	SW	28.3	WSW	41.2	25.7	39.2	1.53	0.14
Aug 16	ESE	39.1	ESE	52.5	35.6	52.0	1.46	0.12
1973 July 17	E	30.4	E	44.3	26.4	41.8	1.58	0.16
1974 Oct 12	E	23.2	E	29.9	20.7	28.2	1.36	0.10
Oct 19	E	25.2	E	36.5	22.5	34.4	1.53	0.14
Oct 30	ENE	22.6	ENE	28.3	19.7	24.6	1.25	0.07
1975 Oct 14	NNE	32.9	ENE	48.9	30.2	45.7	1.51	0.14
Oct 23	ENE	21.6	ENE	35.5	18.9	30.9	1.63	0.17
1976 Aug 24	SE	20.6	S	32.4	18.7	29.2	1.56	0.15
Sept 19	ENE	27.3	ENE	36.0	22.8	31.3	1.37	0.10
1977 Sept 24	ENE	23.7	ENE	33.5	20.6	29.1	1.41	0.11
1978 July 26	E	31.9	E	39.1	27.2	36.9	1.36	0.10
Aug 27	ENE	27.3	ENE	35.5	22.8	30.9	1.36	0.10
Oct 1	E	20.6	E	25.7	18.7	24.3	1.30	0.08
Oct 16	E	23.7	E	28.8	21.4	27.2	1.27	0.07
1979 Aug 2	SW	40.2	SW	55.1	35.3	52.5	1.49	0.13
Sept 23	E	34.0	E	41.2	28.3	38.9	1.37	0.10
1980 July 22	ENE	22.6	E	35.0	20.2	31.8	1.57	0.15
July 27	SW	22.6	SW	29.3	20.6	27.9	1.35	0.10

available data recommended the use of the following expression for a Dines anemometer, from which the maximum gust wind speed is estimated to be the maximum for a 3 second averaging period in an hour.

$$\frac{\hat{V}}{\bar{V}} = \left(1 + 3.7\,\frac{\sigma_V}{\bar{V}}\right)$$

given turbulence intensity as

$$\frac{\sigma_z}{\bar{V}} = \left(\frac{\hat{V}}{\bar{V}} - 1\right)/3.7 \qquad (7)$$

Turbulence intensity for each storm has been evaluated in Table 3 and is given in Figure 3 as a function of wind speed.

4 TROPICAL CYCLONE DATA COMPARED WITH WIND DATA OVER THE SEA

The turbulence intensity of the wind in tropical cyclones as measured at Waglan Island imply a range of wind structure characteristics when fitted to, or compared with, the Deaves and Harris strong wind model. It is not suggested that the Deaves and Harris strong wind model is necessarily appropriate for wind flow over the sea surface in a tropical cyclone, but it is a wind model based on classical log profiles and in which there are well defined relationships between roughness length, friction velocity, drag coefficient, mean and gust wind speed and turbulence intensity profiles, all of which can be related to a surface roughness condition as characterised in Table 1. On Figure 3 three terrain roughness conditions from Table 1 are shown as a function of the turbulence intensity at a height of 50 m.

Inspection of the parameters implied by the Deaves and Harris strong wind model in Figure 3 indicates that as the wind speed increases the characteristics in the wind flow over the sea in a tropical cyclone take on progressively the characteristics of flow over (a) a flat desert at the lower wind speeds, (b) the flow over grass plains, and (c) the flow over trees and suburban housing at the higher wind speeds. In terms of the physical heights of the surface roughness (waves) this progression is not altogether unexpected.

These characteristics can now be compared with currently accepted characteristics of wind flow over the sea as described in §2.2. Possibly the most convenient parameter for comparison is the surface drag coefficient and this comparison is given in Figure 4. At the lower wind speeds the wind flow over the sea in a tropical cyclone is as predicted by Equation 4 from the reviews of Garratt and Wu. However that is where the similarity ends, because at progressively higher wind speeds the wind flow over the sea in a tropical cyclone shows a progressively higher surface drag coefficient, and hence implied higher surface roughness, than is predicted for wind flow over the sea by Equation 4.

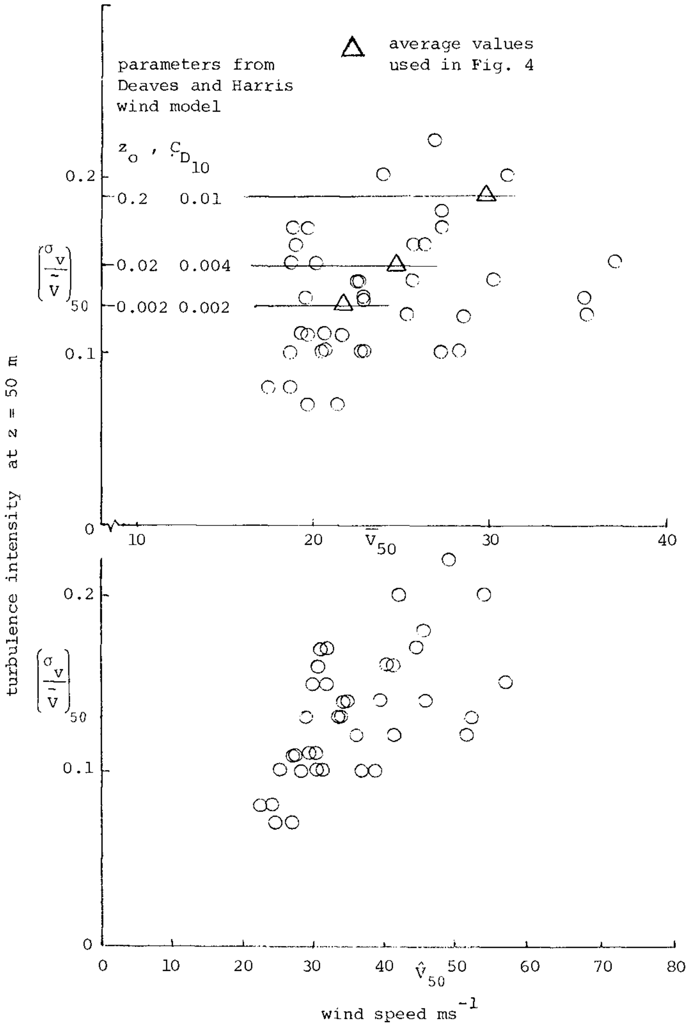

FIG. 3 Turbulence intensity at a height of 50 m above MSL from Waglan Island tropical cyclone data.

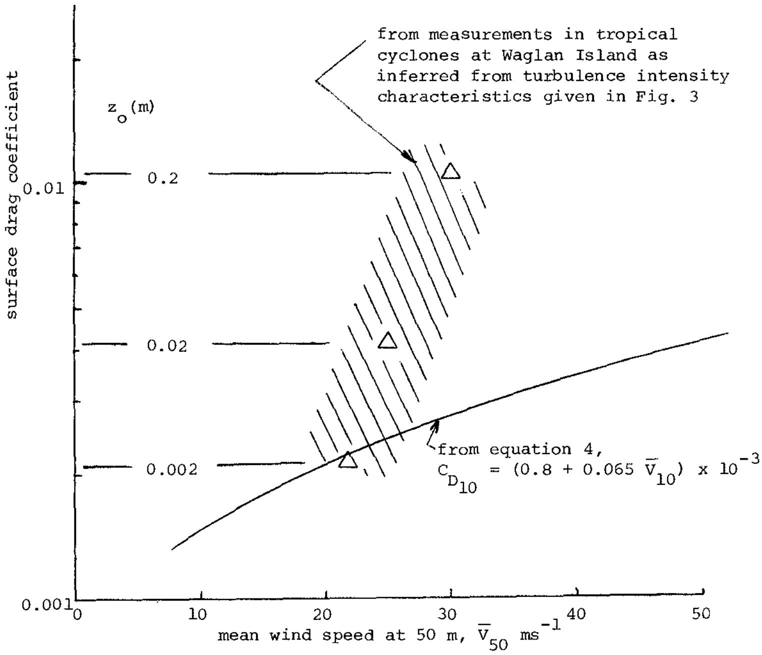

FIG. 4 Surface drag coefficients from Waglan Island tropical cyclone data and the reviews of Garratt (1977) and Wu (1980, 1983).

Further support for this observation is given by Choi (1978) who reported on the mean wind and turbulence characteristics of tropical cyclones in the lower 70 metres of the atmosphere. His work was based on anemometer measurements taken on a tower at Cape D'Aguilar, on a low lying headland stretching out from the southern tip of Hong Kong Island, close to Waglan Island, and with a similar exposure to the Pacific Ocean from where the typhoons approach. Choi fitted log law profiles to data from several tropical cyclones and the values of u_* and z_o are given in Table 4, along with typical values from a monsoon.

TABLE 4

PARAMETERS OF LOG-LINEAR PROFILE OF MEAN WIND SPEEDS IN TROPICAL CYCLONES, AFTER CHOI (1978)

Typhoon	$\bar{V}_{10}$ (ms^{-1})	u_* (ms^{-1})	z_o (m)
Freda	15.0	2.69	0.91
Freda	11.9	3.68	2.30
Rose	13.3	3.71	2.00
Rose	17.7	3.85	1.43
Rose	20.6	4.90	1.64
Dot	15.6	1.90	0.34
Dot	18.6	1.79	0.15
Dina	11.5	2.44	1.25
Monsoon	7.0	0.3	0.05

It can be seen, in comparison with monsoon winds, that u_* is an order of magnitude higher during tropical cyclones, even though wind speeds are only doubled. In the full scale situations the values of z_o reported cannot be taken too seriously because of the difficulty of establishing a zero plane for the site, however the values of u_* can be accurately estimated.

Obviously there are some aspects of the representation of the boundary layer over land and the boundary layer over the sea which do not apply in tropical cyclone or possibly other extreme wind conditions. Whether this is due to the convective conditions found in tropical cyclones, to the shorter wave length in the short fetch wave development, to a model which is simply not applicable to fully aroused sea states, or some other cause must await future investigation.

5 CONCLUSIONS

A study of wind data collected from the Waglan Island anemometer (Hong Kong) during 39 tropical cyclones indicates that turbulence intensity values in excess of 20% at a reference height of 50 m are likely during extreme wind conditions in a tropical cyclone. The implied surface drag coefficient of approximately 0.01 in these extreme wind conditions is consistent with flow over a land surface roughness of trees and suburban housing, but is much higher (by a factor of five) than that predicted by the currently accepted formulae from the reviews of Garratt and Wu for wind flow over a fully developed sea in neutral atmospheric conditions.

Whether these conditions of apparently greater effective surface roughness in tropical cyclones are due to convective conditions, the shorter wave length in the short fetch wave development or some deficiency in the wind model (when applied to wind flows in a tropical cyclone) is yet to be discovered. In the meantime it is concluded, for wind loading design calculations in extreme wind in tropical cyclone conditions, that the mean wind speed and turbulence intensity profiles should be taken as for a surface drag coefficient of 0.01, i.e. for a value of roughness length z_o = 0.20 m in the Deaves and Harris wind model.

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APPENDIX 1

Main equations from the Deaves and Harris (1978) Mathematical Model of the Structure of Strong Winds.

(1) Mean wind speed profile.

$$\bar{V}_z = \frac{u_*}{0.4}\left\{\ln\left(\frac{z}{z_o}\right)+5.75\left(\frac{z}{z_g}\right)-1.88\left(\frac{z}{z_g}\right)^2-1.33\left(\frac{z}{z_g}\right)^3+0.25\left(\frac{z}{z_g}\right)^4\right\} \qquad \text{A1-1}$$

where z is height above ground level

z_o is the roughness length

u_* is the friction velocity, obtained from

$$\frac{V_g}{u_*} = \frac{1}{0.4}\left\{\ln\frac{u_*}{z_o\times10^{-4}}+1\right\} \qquad \text{A1-2}$$

z_g is the gradient height, obtained from

$$z_g = \frac{u_*}{6\times10^{-4}} \qquad \text{A1-3}$$

V_z is the mean wind speed at height z (nominally hourly mean)

$\bar{V}_g$ is the mean gradient wind speed

(2) Turbulence intensity profile,

$$\frac{\sigma_{V_z}}{\bar{V}_z} = \frac{u_*}{\bar{V}_z}\ 2.63\eta\left\{0.538+0.09\ln\left(\frac{z}{z_o}\right)\right\}^{\eta^{16}} \qquad \text{A1-4}$$

where $$\eta = 1-\left(\frac{z}{z_g}\right) \qquad \text{A1-5}$$

σ_{V_z} is the standard deviation of wind speed at height z

(3) Gust wind speed,

The 3 second maximum gust wind speed (which is defined as the maximum wind speed average over 3 seconds occurring in one hour) can, for a Dines anemometer, be expressed as

$$\hat{V} = \bar{V}\left\{1+3.7\left(\frac{\sigma_V}{\bar{V}}\right)\right\} \qquad \text{A1-6}$$