The Seventh Asia-Pacific Conference on Wind Engineering, November 8-12, 2009, Taipei, Taiwan

EXTREME WIND SPEEDS AND WIND LOAD FACTORS FOR HONG KONG

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ABSTRACT

In this paper, recent work directed towards improving the design extreme wind speeds for Hong Kong, is described. The work includes the following aspects: a) a wind-tunnel study to determine appropriate directional correction factors for the Waglan Island data, b) an extreme value analysis of winds from typhoons and tropical storms (up to the 2006 season) using the peaks-over-threshold method, and c) assessment of appropriate wind load factors for ultimate limit states design in Hong Kong, allowing for the wind speed/return period relationship for typhoons, and the preponderance of tall buildings there. An assessment of the effective risk level of current design methods in Hong Kong is also given.

KEYWORDS: HONG KONG, LOAD FACTORS, TYPHOONS

Introduction

The Special Administrative Region of Hong Kong experiences strong winds from both typhoons and non-typhoon events, including monsoons. The effect of typhoons from the South China Sea occurs at the rate of one to two storms per year, and governs the design of structures for wind loading. Extreme wind analyses for Hong Kong, using wind data from both the Hong Kong Observatory and Waglan Island, have been carried out by Chen (1975) Melbourne (1984), Holmes *et al.* (2001) and Lam and To (2009). Davenport *et al.* (1984) also described a Monte Carlo simulation study of typhoon wind speeds based on recorded data on typhoon tracks.

An analysis of typhoon winds, from both Observatory data and that from Waglan Island up to 1999, using the 'peaks over threshold' approach, was described by Holmes *et al.* (2001). The present paper continues that work – it includes typhoons and named tropical storms extended up to the 2006 season, but will focus exclusively on the Waglan Island data. A discussion of the appropriate wind load factor for design of tall structures is given. Current design practice in Hong Kong, and the implied risk levels, is also discussed.

The Waglan Island database and corrections

Wind data is available from 1953 up to the present is available from Waglan Island, a small steep rocky island on the southern extremity of Hong Kong.

Anemometers have been located in a variety of locations, and at various heights above mean sea level. Between 1964 and 1966, the anemometer was in the wake of the lighthouse on the island, and the data from this period is unreliable.

A 1/400 scale model of Waglan Island was manufactured and installed in the boundary-layer wind tunnel at Hong Kong University of Science and Technology (HKUST), to determine correction factors for the topography of the island, for various wind directions. Measurements were made at 22.5 degree intervals for the full 360 degrees azimuth using a hot-wire anemometer. The directional correction factors obtained relate the mean wind speed at each height and location, to the mean wind speed at a reference height of 200 metres. The values of correction factors obtained are shown in Figure 1, as a function of wind direction.

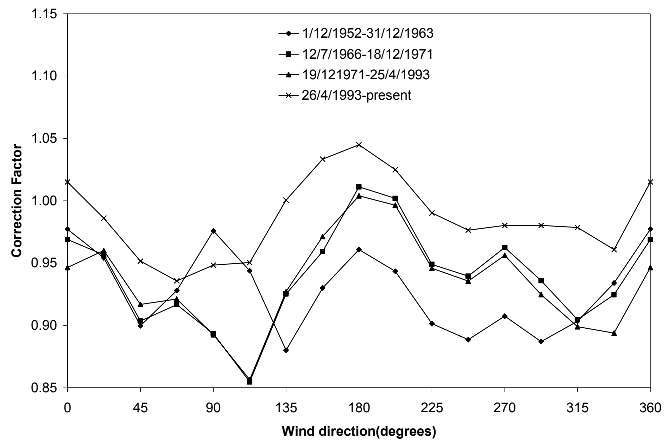

Figure 1: Directional correction factors (anemometer mean/ mean speed at 200 m) obtained from 1/400 scale model at HKUST

No corrections have been made for anemometer response, although it is known that the anemometers of the Dines pressure-tube type generally recorded higher *gusts* than those recorded by the rotating cup type. However, the differences in recorded *hourly mean* wind speeds are believed to be quite small at wind speeds of the magnitudes found in typhoons.

Extreme value analysis methodology

The recorded wind speeds from tropical storms and typhoons recorded at Waglan Island were separated from those generated by other wind types, such as monsoons or thunderstorms, before attempting any analysis of wind speeds for design purposes. This is a good practice, as the winds generated by the different types will generally follow different probability distributions. The database of typhoons and named tropical storms from Waglan Island consists of the maximum recorded mean and peak gust wind speeds from 92 named storms (i.e. tropical storms and typhoons) over a period of 52 years up to 2006 (excluding 1964 –1966). Maximum uncorrected hourly-mean wind speeds greater than 20 m/s from typhoons recorded at Waglan Island in the 1983 to 2006 period are listed in Table 1.

Table 1: Maximum recorded hourly mean wind speeds greater than 20 m/s (uncorrected) from typhoons at Waglan Island (1983-2006)

YEAR	**Typhoon name**	**Hourly mean (m/s)**
1983	***Ellen***	***44.2***
1983	Joe	23.7
1984	Wynne	24.7
1985	Tess	22.1
1986	Wayne	20.1
1987	Lynn	20.0
1989	Brenda	26.2
1989	Gordon	25.2
1989	Brian	21.9
1989	Dan	21.4
1991	Brendan	28.8
1991	Fred	28.1
1992	Chuck	20.8
1992	Faye	26.1
1992	Gary	22.1
1993	Koryn	27.8
1993	Tasha	25.2
1993	Becky	34.0
1993	Dot	22.1
1993	Ira	23.1
1994	Luke	20.8
1995	Helen	28.8
1995	Kent	20.1
1995	Sybil	20.1
1996	Sally	24.2
1997	Victor	30.3
1997	Zita	23.1
1998	Babs	22.5
1999	Leo	25.2
1999	Sam	26.7
1999	***York***	***42.2***
1999	Cam	20.0
2000	Wukong	20.0
2001	Utor	24.4
2002	Hagupit	21.9
2003	Imbudo	23.1
2003	Krovanh	21.4
2003	Dujuan	22.5
2004	Kompasu	24.4
2005	Damrey	22.5
2006	Chanchu	23.1
2006	Prapiroon	21.9

After correction to a height of 200 metres, the mean wind speeds from typhoons have been analyzed using a 'peaks-over-threshold' approach. This can be regarded as a method of fitting the Generalized Extreme Value distribution (GEV), and is a useful method for including all relevant storm data in the analysis. It was previously applied to Hong Kong typhoon winds by Holmes *et al.* (2001). This approach, as described following, was followed for the re-analysis described in this paper.

Extreme wind speeds are usually fitted with one of the family of Generalized Extreme Value Distributions (GEV). The general form of this distribution is as follows (e.g. Holmes, 2007).

$$F_U(U) = \exp\{-[1 - k\,(U-u)/a]^{1/k}\} \qquad (1)$$

where $F_U(U)$ is the cumulative probability distribution function of the maximum wind speed in a defined period (e.g. one year).

In Eq. (1), k is a shape factor, a is a scale factor, and u is a location parameter. When $k < 0$, the G.E.V. is known as the *Type II Extreme Value* (or *Frechet*) Distribution; when $k > 0$, it becomes a *Type III Extreme Value Distribution* (a form of the *Weibull* Distribution). As k tends to 0, Eq. (1) becomes Eq. (2) in the limit. Eq. (2) defines the *Type I Extreme Value*, or *Gumbel, Distribution*.

$$F_U(U) = \exp\{-\exp[-(U-u)/a]\} \qquad (2)$$

The Type III E.V. Distribution, with a positive value of shape factor, k, has an upper limit of the predicted wind speed (equal to $u + a/k$). Physically, this might be related to the thermodynamic upper limits on the strength of tropical cyclones suggested by some authors (e.g. Holland, 1997; Emanuel, 1999). The Type III E.V. distribution is currently used in Australia for extrapolation of extreme wind speeds in both cyclonic and non-cyclonic regions. It has also been proposed for use in the United States to give a better estimate of risk in hurricane regions (Heckert *et al.*, 1998). The Type I, or Gumbel, Distribution also gives unlimited wind speeds, but has been widely used for extreme value prediction of wind speeds.

A fitting approach which makes use only of the data of relevance to extreme wind prediction is the *peaks*, or *excesses, over threshold* approach (e.g. Heckert *et al.*, 1998; Davison and Smith, 1990; Holmes and Moriarty, 1999). One variation of the method is also known as the 'conditional mean exceedence' (CME) method.

The CME method makes use of all wind speeds from independent storms above a particular minimum threshold wind speed, u_0 (say 20 m/s). There may be several of these events, or none, during a particular year. The basic procedure is as follows:

- several threshold levels of wind speed are set : u_0, u_1, u_2, etc. (e.g. 20, 21, 22 …m/s)
- the exceedences of the lowest level u_0 by the maximum storm wind are identified, and the number of crossings of this level per year, λ, is calculated
- the differences $(U-u_0)$ between each storm wind and the threshold level u_0 are calculated and averaged (only positive excesses are counted)
- the previous step is repeated for each level, u_1, u_2 etc, in turn

- the mean excess is plotted against the threshold level
- a scale factor, σ, and a shape factor, k, are determined from the following equations (Davison and Smith, 1990):

$$\text{slope} = \frac{-k}{(1+k)} \qquad \text{intercept} = \frac{\sigma}{(1+k)} \tag{3}$$

Prediction of the R-year return period wind speed, U_R, can then be made from Eq. (4).

$$U_R = u_0 + \sigma[1-(\lambda R)^{-k}]/k \tag{4}$$

In Eq. (4), the shape factor, k, is normally found to be positive (usually around 0.1). As R increases to very large values, the upper limit to U_R of $u_o+(\sigma/k)$ is gradually approached.

When k tends to zero, it can be shown mathematically that Eq. (4) reduces to Eq. (5).

$$U_R = u_0 + \sigma \log_e(\lambda R) \tag{5}$$

Results of the extreme value analysis of typhoon winds for Hong Kong

A summary of the analyses for the Waglan Island typhoon winds (both hourly mean and peak gust at 50 m height) is given in Table 1. It is noted that 'forcing' the shape factor, k, to equal 0, is approximately equivalent to fitting a Type I (Gumbel) distribution to the annual maxima (Holmes and Moriarty, 1999).

Table 2: Results of peaks over threshold analyses of Waglan Island typhoon data (1953-2006)

	Means (200 m)	***Peak gusts*** (50 m)	***Means*** (200 m)	***Peak gusts*** (50 m)
lowest threshold, u_0 (m/s)	20	24	20	24
rate (/year), λ	1.73	1.69	1.73	1.69
scale, σ (m/s)	6.8	9.1	6.2	8.5
shape, k	0.041	0.031	0.0 *	0.0*
20 year R.P. (m/s)	42.3	54.2	42.0	53.9
50 year R.P.(m/s)	47.5	61.5	47.7	61.6
200 year R.P. (m/s)	55.1	72.2	56.3	73.4
1000 year R.P. (m/s)	63.4	84.1	66.3	87.0
$(V_{1000}/ V_{50})^2$	1.78	1.87	1.93	1.99
$(V_{1000}/ V_{50})^{2.5}$	2.06	2.19	2.28	2.37

* The shape factor has been 'forced' to equal 0.0

Values obtained for both the mean wind speeds at 200 m, and peak gusts at 50m, obtained both when the shape factor, k, is free to vary, and when it is forced to be 0.0, are given in Table 2. The latter approach gives higher estimates than those obtained with the positive shape factor, for return periods greater than 20 years. The differences for the 50 year return period are less than 1 m/s, but are about 3 m/s for the 1000-year return period values.

The predictions for hourly mean wind speeds in Table 2 are similar to those reported by Holmes *et al.* (2001), which only included storms up to 1999. During the subsequent seven years, several medium strength storms impacted Hong Kong (e.g. 'Utor', 2001; 'Imbudo' and 'Dujuan', 2003; 'Kompasu', 2004; 'Damrey', 2005; 'Prapiroon', 2005 – see Table 1), but no storms of the strength of 'York' (1999) or 'Ellen' (1983). The 50-year return period value of 47.5 m/s is also quite similar to the value obtained as a gradient wind by Davenport *et al.* (1983), using a simulation approach.

Wind load factors for design

It is the current practice to use a nominal design wind speed in Hong Kong described as a 50-year return period (Buildings Department, 2004a), together with a load factor applied to wind loads of 1.4. Although an established methodology exists for determination of rational load factors for structural design, taking account of all the uncertainties in the estimation of loads, based on structural reliability theory (e.g. Ellingwood *et al.*, 1980; Pham *et al.*, 1983; Holmes and Pham, 1993), such methodologies do not, as yet, seem to have been applied in Hong Kong. For historical reasons, the wind load factor of 1.4 in use in Hong Kong, follows practice in the United Kingdom. However, in the U.K., this factor is applied to non-dynamic structures (for which wind loads increase as the windspeed squared), and for a temperate climate where the extreme winds are primarily produced by extratropical depressions (i.e. Atlantic 'gales') with a lower rate of increase of wind speed with return period. Furthermore, the majority of buildings in Hong Kong are high rise with significant dynamic effects – leading to load effects which vary with windspeed raised to a power of at least 2.5, instead of 2. This, together with the climate differences, suggest that a significantly higher load factor than 1.4 should be used.

An alternative approach to using the 50-year return period with a load factor significantly greater than 1, is to use a high return period wind speed with a load factor of 1.0, as used in Australia and New Zealand (Standards Australia, 2002); in the latter case a 1000-year wind speed is used for tall buildings. In the hurricane-influenced regions of the United States, nominal 50-year wind speeds are currently obtained by dividing high return period values (about 700 year return period) by the square root of the load factor (ASCE, 2006). In future editions of ASCE 7 it is planned to use a basic wind speed with a 700-year return period as the basic wind speed for all buildings, and for all parts of the United States (Irwin, 2009).

Thus a possible wind load factor for Hong Kong could be obtained by considering the square of the ratio of the 1000-year wind speed to the 50-year value. These values are shown in the second last row of Table 2, and indicate a factor of 1.8 to 2.0. However, such values would not allow for the fact that dynamic resonant response for tall buildings is significantly higher at the higher windspeeds. This can be accounted for by taking the ratio of wind speeds to the power of 2.5, as is done in the last row of Table 2. This leads to a load factor of 2.1 to 2.3, based on a mean wind speed at 200 metres height of 47 to 48 m/s.

Based on a similar analysis, Lam and To (2009) have suggested load factors of 1.68 to 1.79 in order to adjust the effective return period to 975 years, (assuming wind loads vary as wind speed squared). A return period of 975 years arises by setting the probability of exceedence in a nominal building lifetime of 50 years, as 0.05, or 5%.

Effective risk level of current design wind speeds in Hong Kong

In the current Hong Kong Code of Practice (Buildings Department, 2004a), the specified hourly mean wind speed is 59.5 m/s at a height of 500 metres. When adjusted to a height of 200 metres, using the power law exponent of 0.11 adopted in the Hong Kong C.P., this is equivalent to:

$$59.5 \times \left(\frac{200}{500}\right)^{0.11} = 53.8 \quad \text{m/s}$$

This value is about 13% higher than the value for 50-year return period of 47.5 m/s given in Table 1. The difference can be explained by two different reasons:

- The design wind speed has been increased in the Code by a factor of 1.05 to account for general uncertainties in typhoon wind *profiles* (Buildings Department, 2004b),

- The calculated 50-year wind speed is based on analysis of hourly-mean Waglan Island data for the period from 1953 to *1980*; this gives a higher value by about 8% from that obtained from the 1953 to *2006* period (as used for Table 1).

These two effects together can be regarded as being equivalent to increasing the effective load factor by 1.27 to 1.28 (= 1.13^2) for quasi-static wind loading – roughly equal to the increase of 1.15^2 used as a 'cyclone factor' in Australia up to 1989. For dynamic structures the increase is roughly 1.35 (= $1.13^{2.5}$). When these factors are used to derive equivalent wind speeds, the design wind speeds in the Hong Kong Code of Practice have effective return periods of 1000 to 700 years (based on the 1953-2006 dataset). This is consistent with the practice for tropical-cyclone affected locations in Australia, and hurricane regions of the United States, although derived somewhat differently, and perhaps is a little 'opaque'.

It is also noted that the design value of mean wind speed at 200 metres height of 53.8 m/s implied in the Hong Kong C.P. appears to have a return period of 150-160 years, not 50 years, based on the 1953 to 2006 data set used for the present analysis.

Conclusions

A re-analysis of extreme wind speeds in Hong Kong using data from 1953 to 2006, has given an estimated 50-year return period wind speed, at 200 metres height above the ocean, of 47 to 48 m/s, apparently a considerably lower value than that currently used for design of tall buildings in Hong Kong, but similar to other analyses. A more rigorous assessment of the appropriate wind load factor to be used with loads calculated from V_{50}, suggests a value of about 2.2, rather than the currently-used 1.4.

However, when a closer look is taken at the current wind speeds used for design in the current Hong Kong Code of Practice, they actually have a return period of around 150 years, based on recorded anemometer data from 1953 to 2006. When these values are used for calculation of wind loads with the present load factor of 1.4, the return period of the equivalent design wind speed is in the range 700 to 1000 years. Noting that the American Standard (ASCE 7) in future editions will shortly switch to a 700-year return period basic wind speed (coupled with a wind load factor of 1.0), for all buildings, and that the Australian /New Zealand Standard uses 1000-year wind speeds for tall buildings, the implied risk level in Hong Kong is, in fact, similar to those for buildings in the United States and Australia.

References

American Society of Civil Engineers (2006), Minimum design loads for buildings and other structures, ASCE/SEI 7-05, A.S.C.E., New York.

Buildings Department (2004a), Code of practice on wind effects in Hong Kong, Buildings Department of Hong Kong.

Buildings Department (2004b), Explanatory materials to the Code of practice on wind effects in Hong Kong, Buildings Department of Hong Kong.

Chen, T.Y. (1975), "Comparison of surface winds in Hong Kong", Hong Kong Royal Observatory, Technical Note 41.

Davenport A.G., Georgiou, P.N., Mikitiuk, M., D. Surry and G. Lythe (1984), "The wind climate of Hong Kong", Proceedings, Third International Conference on Tall Buildings, Hong Kong and Guangzhou , 1984.

Davison, A.C. and Smith, R.L. (1990), "Models for exceedances over high thresholds", Journal of the Royal Statistical Society, Series B, 52, 339-442.

Ellingwood, B.R., Galambos, T.V., McGregor, J.G. and Cornell. C.A. (1980), Development of a probability-based load criterion for American National Standard A58, National Bureau of Standards Special Publication 577.

Emanuel, K.A. (1999), "Thermodynamic control of hurricane intensity", Nature 401, 665-669.

Holland, G.J. (1997), "The maximum potential intensity of tropical cyclones", Journal of Atmospheric Sciences, 54: 2519-2541.

Holmes, J.D. and Moriarty, W.W. (1999), "Application of the generalized Pareto distribution to extreme value analysis in wind engineering", Journal of Wind Engineering & Industrial Aerodynamics, 83, 1-10.

Holmes, J.D. and Pham, L. (1993), "Wind-induced dynamic response and the safety index". Proceedings, 6th International Conference on Structural Safety and Reliability, Innsbruck, Austria, August 9–13, 1993, 1707–1709, A.A. Balkema.

Holmes, J.D., Hitchcock, P., Kwok, K.C.S. and Chim, J.K.S. (2001), "Re-analysis of typhoon wind speeds in Hong Kong", Fifth Asia-Pacific Conference on Wind Engineering, Kyoto, Japan, October 21~24.

Irwin, P.A. (2009), "Wind engineering research needs, building codes and project-specific studies", 11th Americas Conference on Wind Engineering, San Juan, Puerto Rico, June 22-26, 2009.

Lam, K.M. and To, A.P. (2009), "Statistical analysis of extreme wind speeds in Hong Kong and Macau", Hong Kong Institution of Engineers.Transactions, 16, 1-8.

Melbourne, W.H. (1984), "Design wind data for Hong Kong and surrounding coastline", Proceedings, Third International Conference on Tall Buildings, Hong Kong and Guangzhou , 1984.

Pham, L., Holmes, J.D. and Leicester, R.H. (1983), "Safety indices for wind loading in Australia", Journal of Wind Engineering and Industrial Aerodynamics, 14, 3-14.

Standards Australia (2002), Structural design actions. Part 2: Wind actions, Standards Australia, Sydney, and Standards New Zealand, Wellington. Australian/New Zealand Standard AS/NZS1170.2:2002.