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An Extensive Evaluation of the Proposal for "Unified Terrain Categories Exposures and Velocity Profiles" by Choi (2009)

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Keywords: Typhoon Sally, Typhoon Muifa, Hurricane Ike, tall buildings, power-law exponent, roughness length, gradient height, displacement height, terrain exposures, velocity profiles.

I. INTRODUCTION

Building or structural damages by storms, whether they are tropical or extra-tropical cyclones, require an estimation of wind speed. Numerous methodologies have been proposed and used (see, e.g. Wieringa, 1992, Zhou and Kareem, 2002, and Irwin, 2006). Most recently, Choi (2009) has proposed his "Unified Terrain Categories Exposures and Velocity Profiles" as presented in Table 1. The purpose of this study is to evaluate Table 1.

Table 1 : Terrain Categories and Related Parameters as proposed by Choi (2009)

Category	Exposure (description)	Roughness Length, meters	Power-law exponent	Gradient Height,meters	Displacement Height, meters
Cat I	Open water (open sea or lake and coastal areas with few obstructions)	0.002	0.103	250	5
Cat II	Open country (terrain with scattered obstructions up to 10 m high. Rural areas with a few low rise buildings)	0.04	0.15	350	5
Cat III	Forest/Sub-urban scattered low (3-5 m) buildings (numerous closely spaced 3-5 m obstructions)	0.2	0.198	450	10
Cat IV	Urban, large town (many medium height (10-50 m) buildings)	0.5	0.241	500	15

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Cat V	City (medium height buildings mixed with tall (50m+) buildings)	1.0	0.289	550	20
Cat VI	City center (concentration of very tall buildings mixed with other buildings)	>=2	0.362	650	30

II. AN EVALUATION DURING TYPHOON MUIFA IN 2011

During Typhoon Muifa in 2011 there are 3 studies which can be used for our evaluation. They are:

a) Wind Measurements at Two Locations on the Sutong Bridge

According to Xu et al (2013), the SutongBridge across the low reaches of the Yangtze River in China is a cable-stayed bridge with its longest span, which is under constant monitoring because of tropical cyclones and other strong winds. During Typhoon Muifa in 2011, there were two anemometers on the bridge. The mean wind speed measured at 76m was 17.08 m/s and at 300.4 m 19.58 m/s, respectively. Using the power-law wind profile formula (see, e.g. Hsu, 1988), we have

$$U2/U1 = (Z2/Z1)^p \qquad (1)$$

$$Z2 > Z1$$

$$P = \text{Ln}\,(U2/U1)/\,\text{Ln}\,(Z2/Z1) \qquad (2)$$

So that,

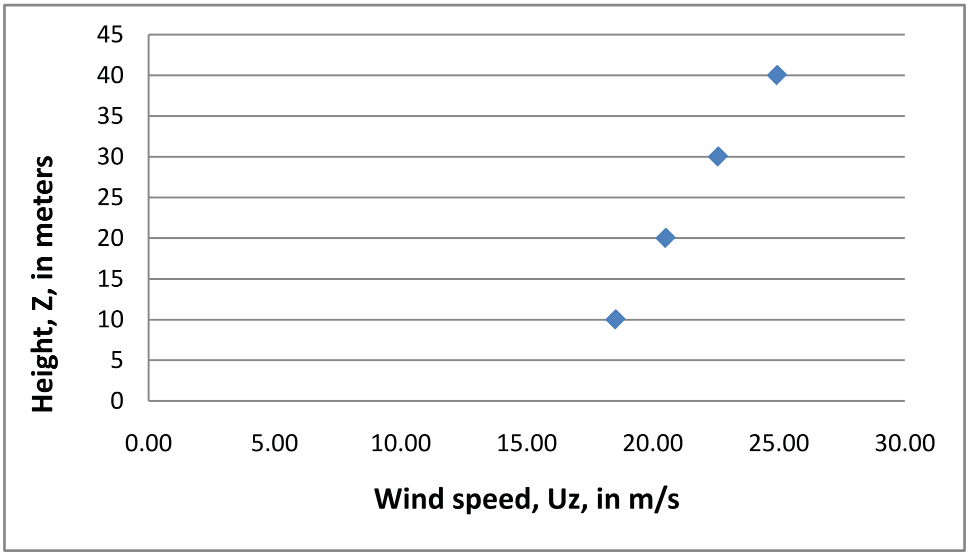
$$p = \text{Ln}\,(19.58/17.08)/\text{Ln}\,(300.4/76) = 0.099 = 0.100$$

Note that U2 and U1 are the wind speeds at height Z2 and Z1, respectively. P is the exponent of the power law.

Now, compare this over-water p (=0.100) with that in Table 1 for open water in Category I in which p = 0.103, we can say that the agreement is excellent. Note that the p (=0.10) value has been measured over the Sicily Strait by Hsu(1988), over the Gulf of Mexico by Hsu et al. (1994) under fair weather condition and by Hsu (2011) under hurricane condition.Note also that these measurements on the Sutong Bridge are unique in that it was over a large (the Yangtze)river.

b) Wind Profile Measurements on the East Coast of Shanghai, China

During Typhoon Muifa in 2011, Peng et al (2013) present a study with the measurements of the wind speed at 4 levels from 10 to 40 meters. These data are plotted in Fig. 1.



(Data Source : Peng et al, 2013)

Figure 1 : Measurements of the wind speed at 4 levels from 10 to 40 m on the east of Shanghai, China, during Typhoon Muifa in 2011

While the power law has been discussed above, the log law is presented as follows:

In the atmospheric boundary layer, vertical distribution of the wind speed (under strong wind conditions so that the thermal effects may be neglected, see Hsu, 2003) can be formulated according to the logarithmic wind profile (e.g. Panofsky and Dutton, 1984) as:

$$U_z = (U^*/k) \ln((Z-d)/Z_0) \qquad (3)$$

Where Uz is the wind speed at height Z, U* is the friction velocity, k (=0.4) is the von Karman constant, d is the displacement height, and Z0 is the roughness length.

Note that when Z is much larger than d, Eq. (3) may be reduced to

$$U_z = (U^*/k) \ln(Z/Z_0) \qquad (4)$$

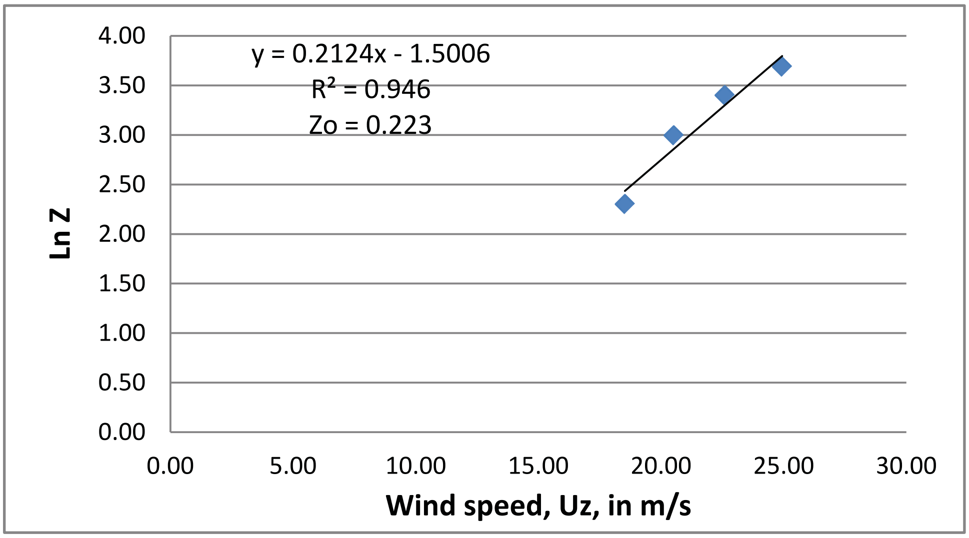
Statistically, Eq.(4) can be written as

$$\ln Z = \ln Z_o + (k/U^*)\, U_z \qquad (5)$$

$$Y = a_0 + a_1 X$$

Where $Y = \ln Z$, $X = U_z$, and $Z_o = \mathrm{Exp}(a_0)$ (6)

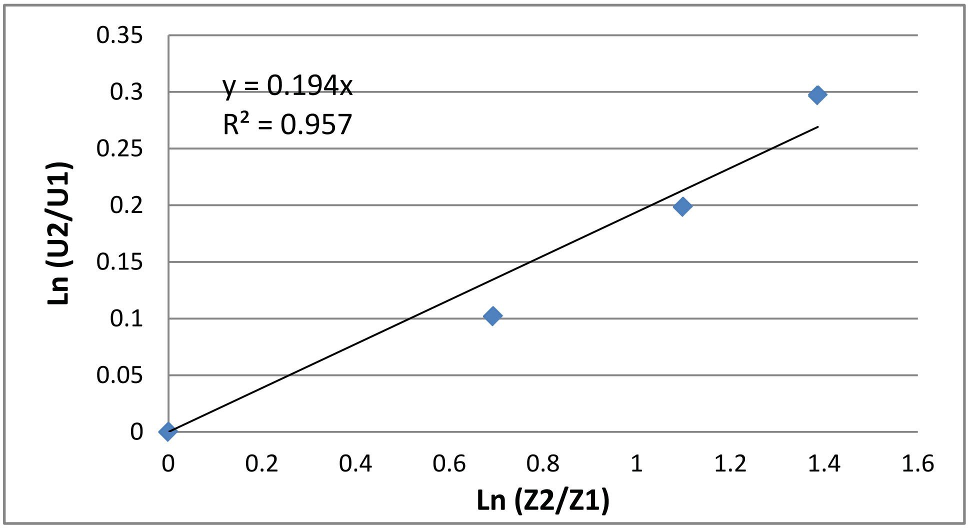
Analysis of the log law is presented in Fig. 2. Since approximately 95 per cent of the wind speed variation with height can be explained by this law (because $R^2 = 0.95$), we can get Zo = 0.223.



(Data Source : Peng et al, 2013)

Figure 2 : Verification of logarithmic wind profile during Typhoon Mufia in 2011 on the east coast of Shanghai, China

Analysis of power law is provided in Fig. 3, which demonstrates that nearly 96 per cent of the wind speed variation with height can be explained by the power law so that p = 0.194. Note that since R2 is higher for the power law than that for the log law, we can say that the former is as good as the latter for engineering applications.



(Data Source : Peng et al, 2013)

Figure 3 : Verification of power-law wind profile during Typhoon Mufia in 2011 on the east coast of Shanghai, China

Now, comparison of these $Z_o = 0.223$ and $p = 0.194$ values to those in Table 1, we can see that the measurement site in Peng et al (2013)was located at Category III. Since values of Zo and p are consistent with those provided in Table 1, we can say that Cat. III is verified.

c) *Wind speed measurements at 494 m atop the Shanghai World Financial Center during Typhoon Muifa in 2011*

An et al (2012) present their wind measurements atop the Shanghai World Financial Center (SWFC) during Muifa. The maximum 10-min mean wind speed reaches 32.97 m/s at 494 m on the rooftop. With this data we can evaluate Cat. VI using Table 1 that p = 0.198 for Cat. III. First, we need to estimate the wind speed at 450 m by applying the power law as follows:

$$U_{450m} / U_{10m} = (450/10) \wedge 0.198 = 2.12$$

$$U_{450m} = 18.53 * 2.12 = 39.37 \text{ m/s}$$

This value is expected to be the same at 650 m over SWFC.

Now, the wind speed at 494 m atop SWFC is estimated to be

$$U_{494m} = U_{650m} * (494/650) \wedge 0.362 = 39.37*0.91 = 35.65 \text{ m/s}$$

Since the difference between estimated wind speed (35.65 m/s) and the measured (32.97) is approximately 8 per cent, which is within the 10 percent margin of error for the composite accuracy of the field measurement in wind speed (see www.ndbc.noaa.gov) , we can say that Table 1 is evaluated to be useful.

d) *Upper-air Measurements from Shanghai during Muifa*

As indicated in Table 1, the gradient height over a large city is 650 m. Since there is no wind measurement at this altitude at present time, we employ the routine upper-air sounding called rawinsonding instead. According to Geer (1996), rawinsonde is a method of upper-air observation consisting of an evaluation of the wind speed and direction, as well as temperature, and humidity aloft by means of a balloon-borne radiosonde (instrument package) tracked utilizing position change as determined by directional radio techniques. Note that rawinsonde measurements are routinely available twice per day at many places around the world including Shanghai, China (see www.ncdc.noaa.gov).

Before the analyses of upper-air data are performed, the concept of virtual potential temperature, θv, needs to be discussed briefly, since it can serve as a stability criterion for an atmosphere with a moisture gradient.For more detail, see Stull (1988). For our analyses, we need to know that when θvis constant, the atmospheric boundary layer is statically neutral. When it decreases with height, the atmosphere is statically unstable. When it increases with elevation, the atmosphere is statically stable. Since the power-law wind profile is valid within a neutral boundary layer, we need to plot this virtual potential temperature value with height so that the gradient height can be determined.

Figs. 4 thru 9 show our results during Typhoon Muifa in 2011 near Shanghai. It can be seen from Figs. 6 and 9 that the average gradient height during these two rawisondings is (677 + 611)/2 = 644 m, which is close to the value of 650 m as proposed in Table 1 for Category VI.Note that at 12Z on 06 August 2011, the wind was light and variable near the ground as shown in Figs. 4 and 5, but at 611 m, the wind speed was 17 m/s and direction from 40 degrees. Similar condition was prevailed 12 hours later (Figs. 7 and 8), but the direction was from 315 degrees with a speed of 7.2 m/s near the ground. At 611m, the speed increased to 26.3 m/s and the direction was from 340 degrees.

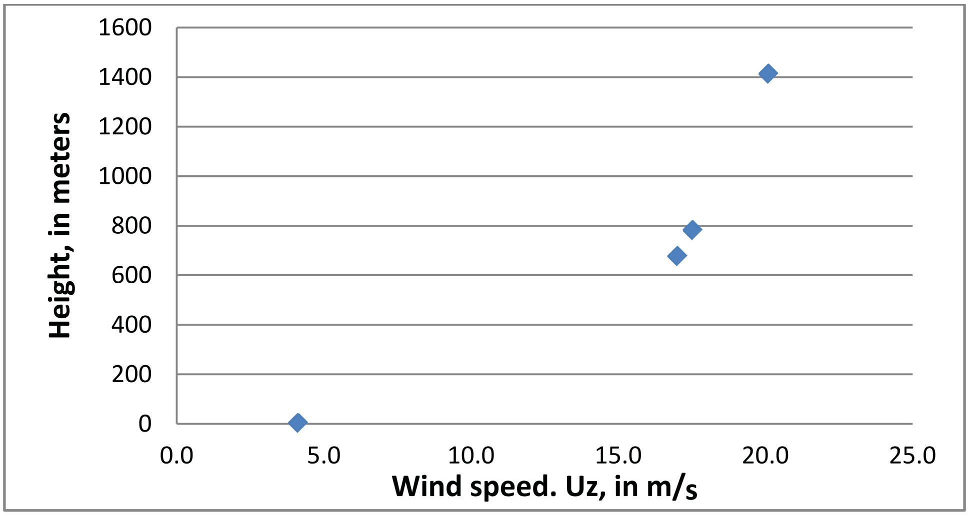


Figure 4 : Rawinsonding of wind speed from Shanghai, China, at 12Z on 06 Aug 2011 during Typhoon Muifa

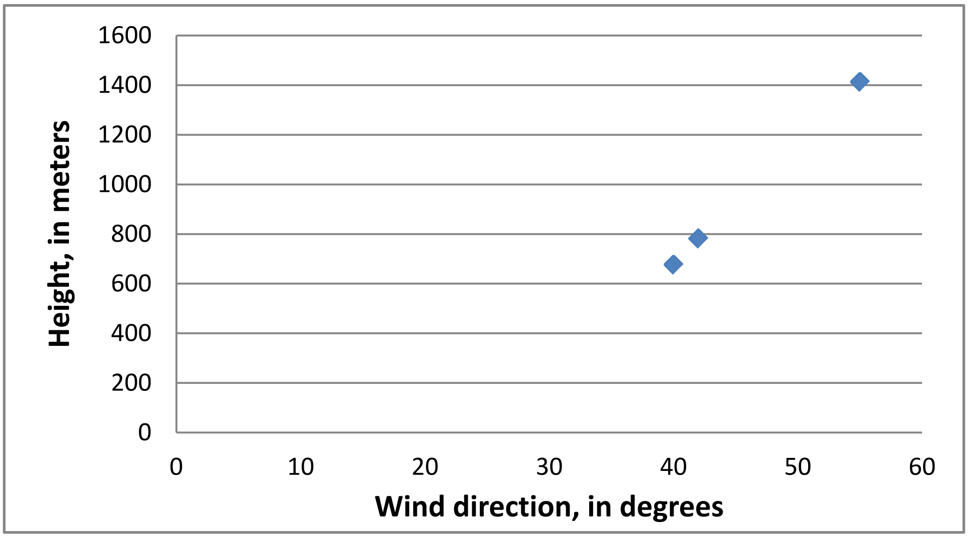


Figure 5 : Rawinsonding of wind direction from Shanghai, China, at 12Z on 06 Aug 2011 during Typhoon Muifa

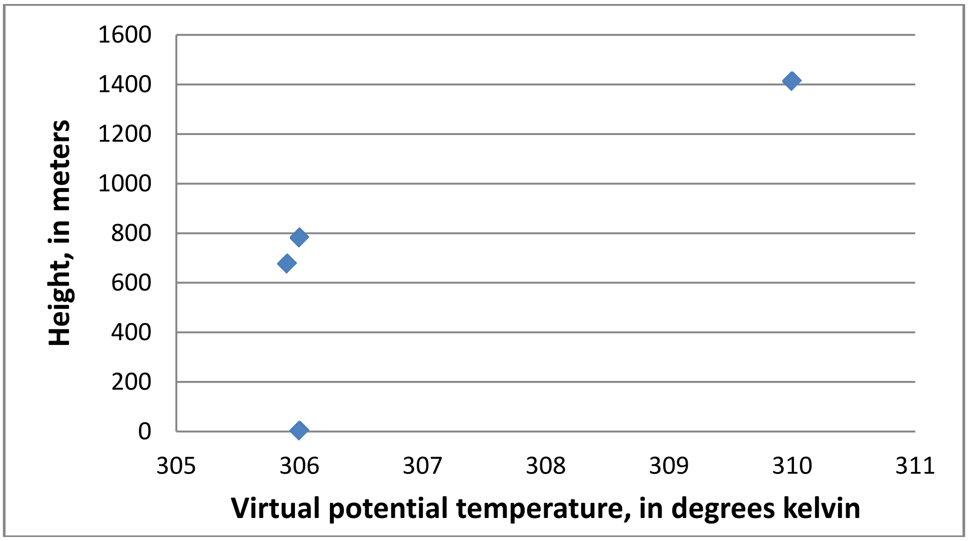


Figure 6 : Rawinsonding of virtual potential from Shanghai, China, at 12Z on 06 Aug 2011 during Typhoon Muifa

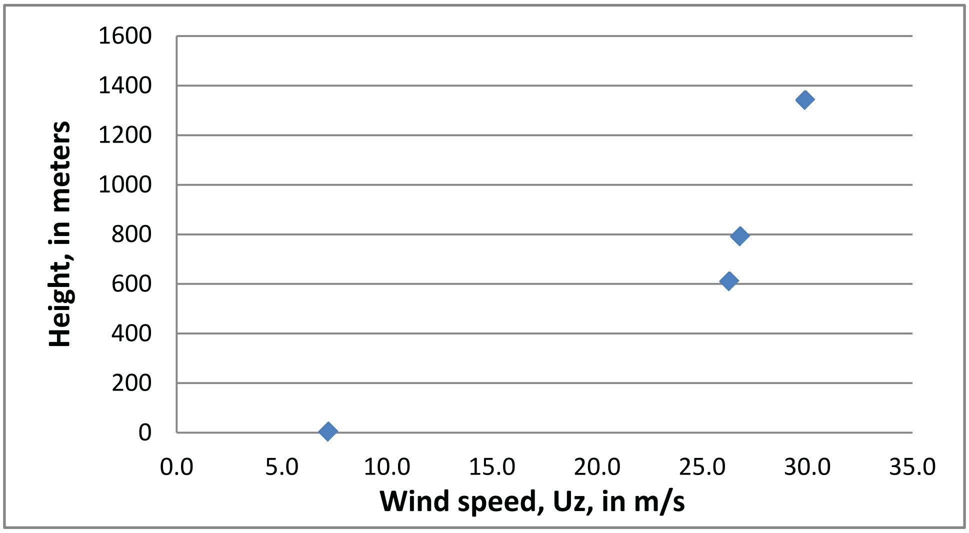


Figure 7 : Rawinsonding of wind speed from Shanghai, China, at 00Z on 07 Aug 2011 during Typhoon Muifa

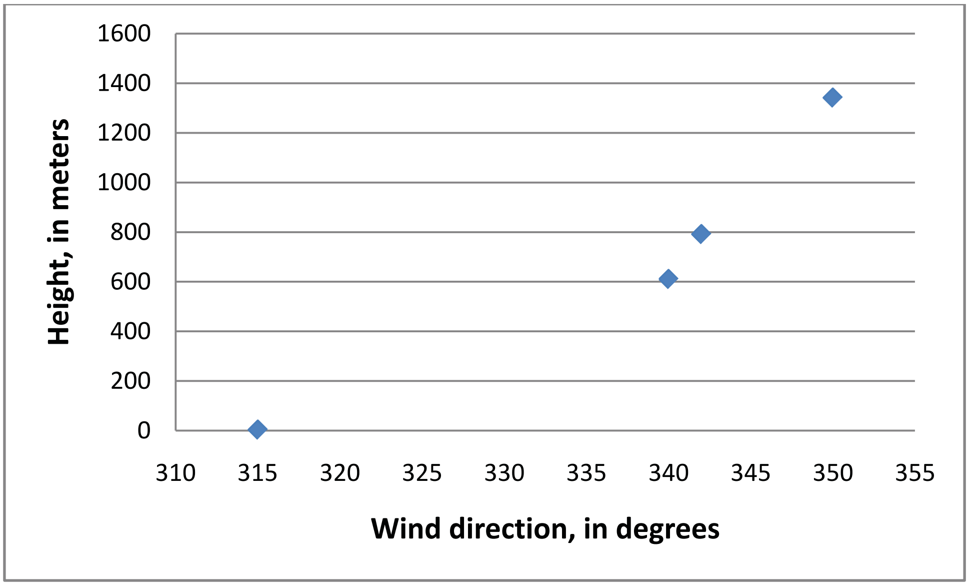


Figure 8 : Rawinsonding of wind direction from Shanghai, China, at 00Z on 07 Aug 2011 during Typhoon Muifa

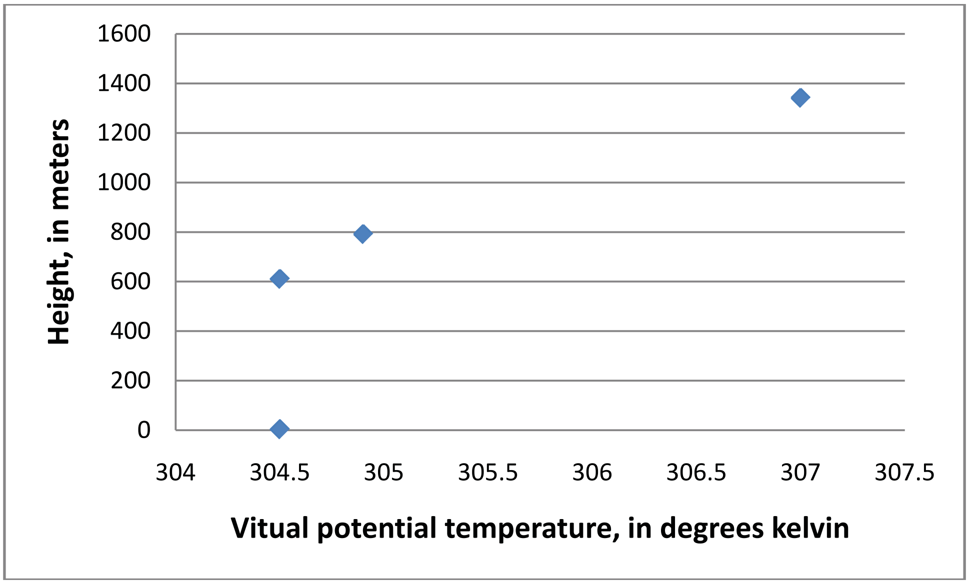


Figure 9 : Rawinsonding of virtual potential temperature from Shanghai, China, at 00Z on 07 Aug 2011 during Typhoon Muifa

III. AN EVALUATION USING MEASUREMENTS IN NEW YORK CITY

a) Validation of The Power-Law Exponent

Hanna et al (2007) present wind measurements during the Manhattan Madison Square Garden in New York City (NYC), USA, urban field experiments during 2005 suitable for our evaluation. Specifically, on 10 March 2005, there were 3 wind speed and direction measurements on three rooftops ranging from 34 to 229 m as shown in Fig. 10. A validation of the power law based on Eq. (1) is presents in Fig. 11, which also indicates that the exponent is determined to be 0.35. This value is close to 0.362 as proposed in Table 1 for Category IV.

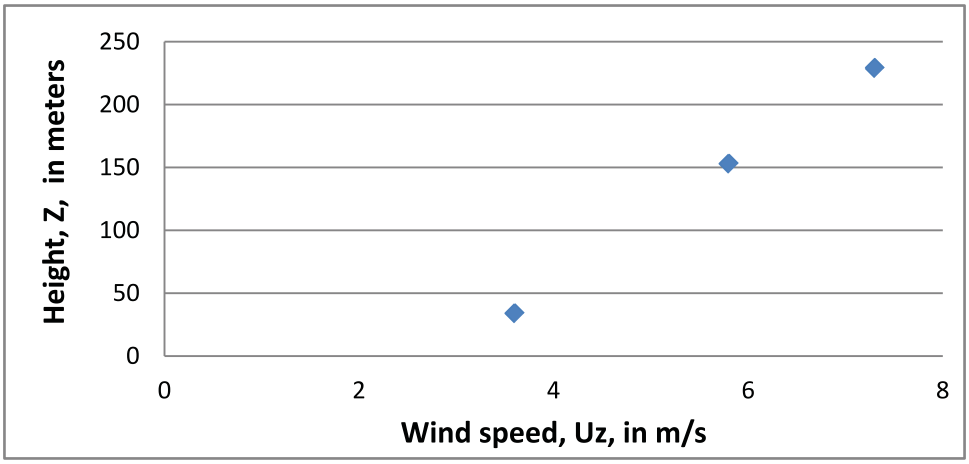


Figure 10 : Measurements of the wind speed on 3 rooftops in New York City by Hanna et al. (2007, Table 3)

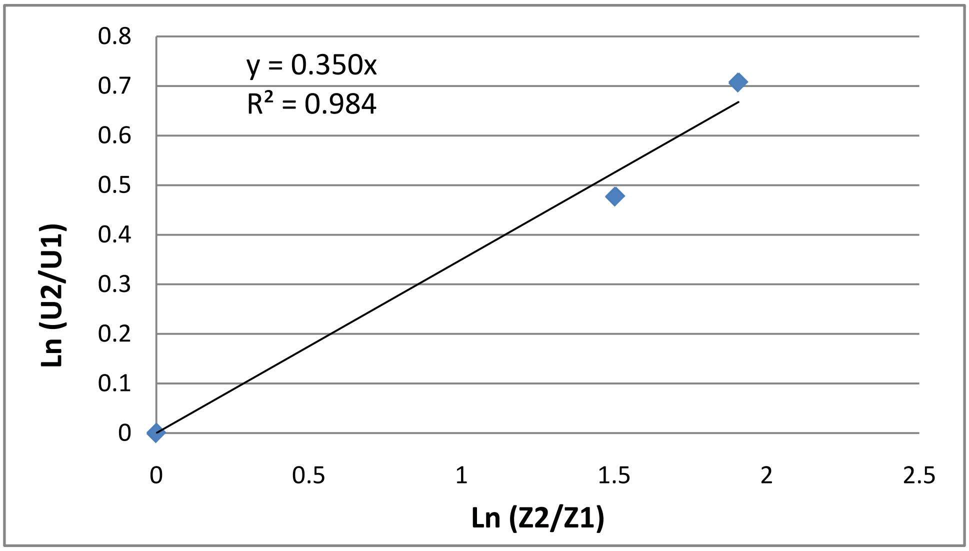


Figure 11 : Validation of the power-law wind profile based on data provided in Figure. 10 in New York City

b) Verifications of Wind Speed at 3 Elevations

Hanna et al (2007) also provided the wind measurement of 6.2 m/s at the standard 10 m height from nearby JFK Airport. We can now evaluate Table 1 using this JFK data as follows:

First, we need to calculate the wind speed at the gradient height for Category II such that, from Eq. (1),

$$U_{350m} = U_{10m} * (350/10) ^\wedge 0.15 = 6.2 * 1.70 = 10.6 \text{ m/s},$$

From Table 1, this value is expected to be the same as that of the wind speed at 650 m over NYC. So, we set $U_{650m} = 10.6$ m/s tocompute the wind speeds located at the three rooftops.

For the rooftop at 229m, we have

$$U_{229m} = U_{650m} *(229/650) ^\wedge 0.362 = 10.6 * 0.69 = 7.3 \text{ m/s},$$

$$U_{153m} = U_{650m} *(153/650) ^\wedge 0.362 = 10.6 * 0.59 = 6.3 \text{ m/s, and}$$

$$U_{34m} = U_{650m} *(34/650) ^\wedge 0.362 = 10.6 * 0.34 = 3.6 \text{ m/s}.$$

These computed values are listed in Table 2 so that they can be compared to the measurements as provided in Hanna et al (2007). Since the margin of error in wind speed measurement is 10 % as stated above, we can say based on Table 2, that the agreements are excellent and Table 1 is evaluated here as useful.

Table 2 : Comparisons between the computed and measured wind speeds at 3 heights in NYC (Data source: Hanna et al, 2007)

Rooftop height, m	Measured Wind speed,m/s	Computed Wind speed, m/s	Difference in Per cent
229	7.3	7.3	0 %
153	5.8	6.3	8 %
34	3.6	3.6	0 %

IV. AN EVALUATION USING MEASUREMENTS IN HOUSTON, TEXAS, DURING HURRICANE IKE IN 2008

When Hurricane Ike passed over the City of Houston, Texas, in September 2008 (see Berg, 2008), there were two wind speed measurements at 20 and 60 meters on a 91 meter communication tower (see Schade, 2012)which are useful for our evaluation as follows:

a) A Comparison of Boundary-layer Parameters with Table 1

According to Schade (2012), several boundary-layer parameters are available for the comparison as shown in Table 3. It can be seen that the Tower in Houston is located in Category V. While both values of roughness parameter and power-law exponent are in excellent agreement, the displacement is not. A recent study of zero-plane displacement height, d, in a highly built-up area of Tokyo shows that the value of d may not be determined from the average building height because ofthe large difference in building heights (see Tanaka et al., 2011). Therefore, values of the displacement height as listed in Table 1 needto be further evaluated. But, for now, it is listed only as a general guide.

Table 3 : A comparison of boundary-layer parameters. Source Roughness

Source	Roughness Length, Zo, m	Power-law Exponent, p	Displacement Height, m
Houston Tower	1.0	0.29	8
Table 1	1.0	0.289	20

b) A Comparison of Wind Speed Measurements

In order to evaluate the tower measurements from Houston, we need to first determine the power-law exponent from nearby Hobby Airport, which was not exactly located in open country but between Categories II and III. This is accomplished as follows:

According to Hsu (2013), the power-law exponent, p, can be determined from the 5-second gust over 2 minute (sustained wind speed) period as used in wind speed measurements by the Automated Surface Observing System (ASOS) station at airport worldwide such that,

$$G = 1 + 2.04\,P \qquad (7)$$

Where G is the gust factor (the ratio of 5-s gust to 2-min sustained wind speed) and p is the power-law exponent. Fig. 12 shows that since G = 1.3672 at Houston Hobby Airport, P = 0.180, indicating this location was between Categories II and III. Because there is no further classification, we need to produce the statistical relationships amongst roughness length, power-law exponent and the gradient height. On the basis of Table 1, these relationships are analyzed and presented in Figs. 13 through 15.

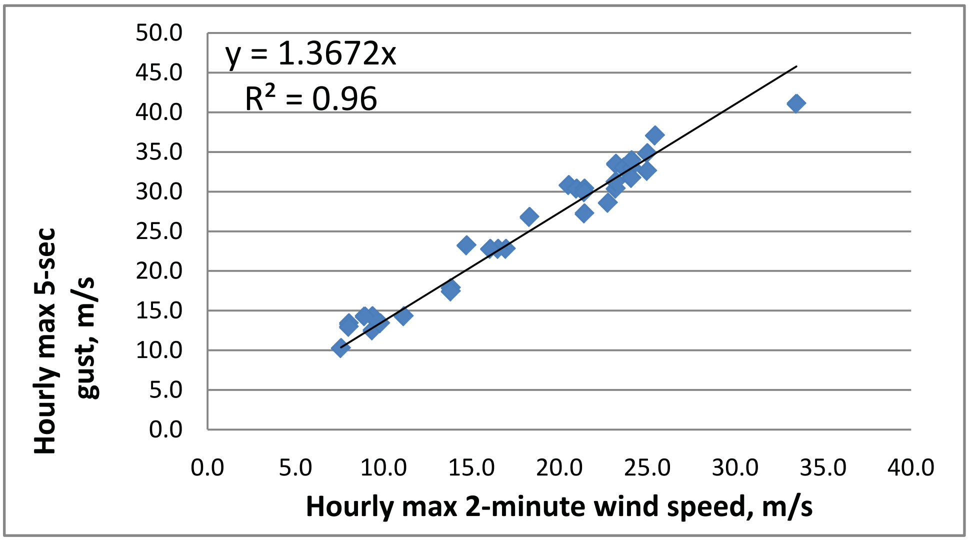
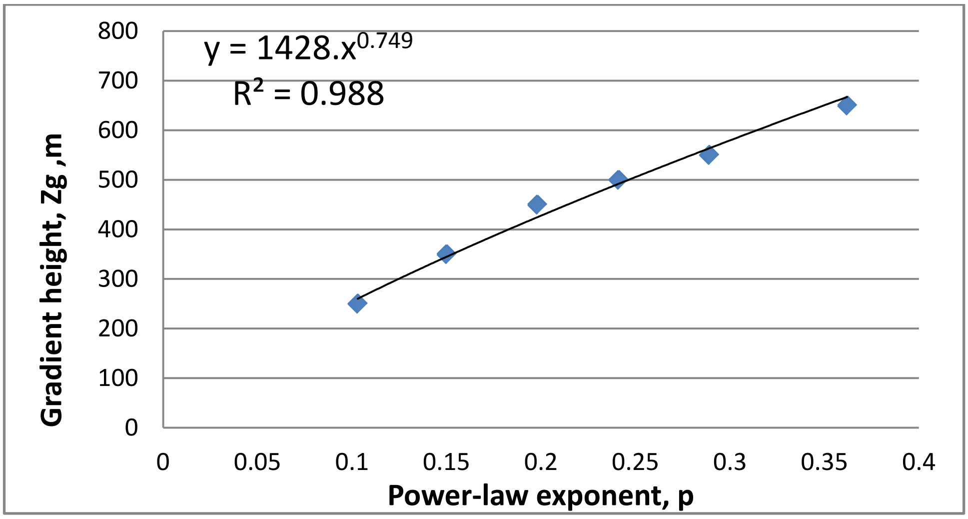
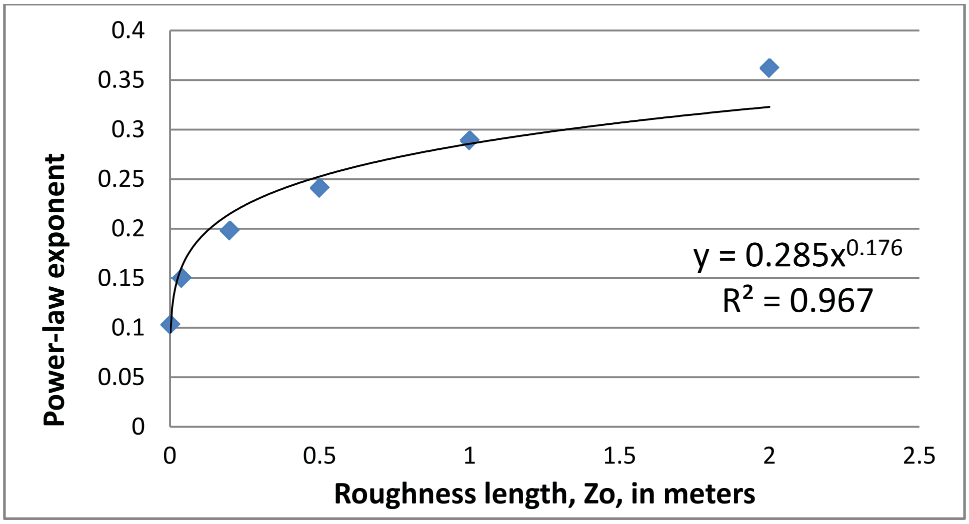


Figure 12 : Relationship between sustained wind speed and gust on 12-13 September 2008 in Houston Hobby Airport during Hurricane Ike



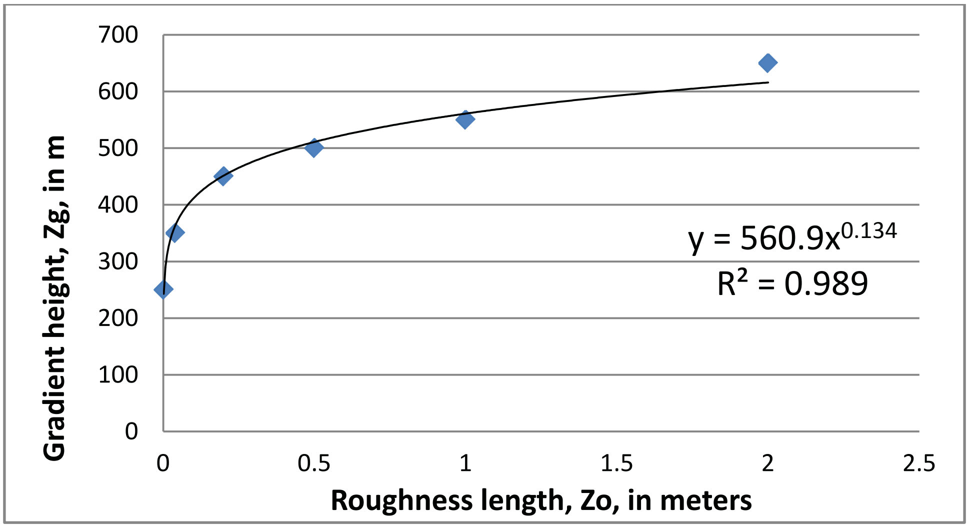
(Data Source : Choi, 2009)

Figure 13 : Relationship between the gradient height and power-law exponent



(Data Source : Choi, 2009)

Figure 14 : Relationship between roughness length and power-law exponent



(Data Source : Choi, 2009)

Figure 15 : Relationship between roughness length and gradient height

With these methods we can compute the wind speeds at the two heights on the Houston tower as follows:

- Based on Fig. 13, given p = 0.180 for Houston Hobby Airport, the gradient height is estimated to be 395 m;
- From Fig. 12, the max sustained 2-min wind speed over Hobby was approximately 34 m/s. Therefore the wind speed at the gradient height of 395 m over Hobby Airport is

$$U_{395m} = U_{10m} *(395/10) \wedge 0.18 = 34 * 1.94 = 66 \text{ m/s},$$

According to Schade (2007), the mean turbulence intensity was 0.29 for the tower. According to Hsu (2013), the power-law exponent, p, is numerically equal to the turbulence intensity. We can assign p = 0.29 for this tower location. Thus, from Fig. 13, the gradient height over the tower is 565 m. Now, we can now compute the wind speed at 60 m at the tower to be

$$U_{60m} = U_{565m} *(60/565) \wedge 0.29 = 66 * 0.52 = 34 \text{ m/s}.$$

Similarly, the wind speed at 20 m on the tower is computed as

$$U_{20m} = U_{565m} *(20/565) \wedge 0.29 = 66 * 0.38 = 25 \text{ m/s}.$$

A comparison of these estimations against the measurements is presented in Table 4. It is found that the agreement is excellent, indicating that our methodology as provided above is operational.

Table 4 : A comparison of wind speed at 2 levels during Hurricane Ike in 2008

Height, m	Estimated wind Speed, m/s	Measured wind Speed, m/s	Difference In per cent
60	34	33	3%
20	25	25	0%

V. An Evaluation using mean Building Height as Input

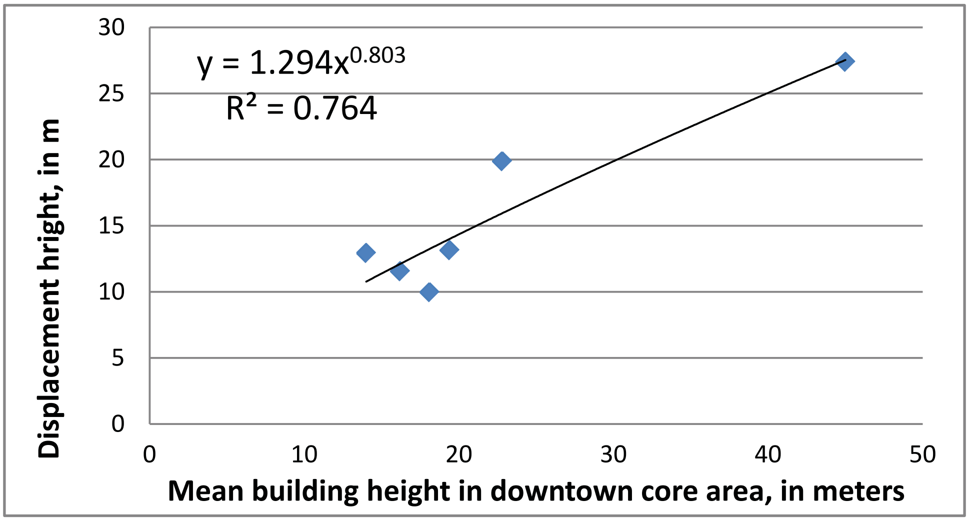
As stated above, the construction of few super tall buildings (building height > 300 m) in several cities makes the estimation of displacement difficult. However, for many urban areas, it is still useful to employ the mean building height as an input to estimate the displacement height. This is done as follows:

- According to the data as provided in Burian et al (2005), which is listed in Table 5, we can say that the displacement height is approximately 72 per cent of the mean building height in the downtown core areas in the cities as studied. This value is reasonably close to that of 80 % as suggested by Panofsky and Dutton (1984, P.376), since the difference is about 10 %.

Table 5 : Data for the displacement height and mean building height in several cities in USA (Data source: Burian et al, 2005)

City	Mean building Height in Downtown, m	Displacement Height, d, m	Ratio
Los Angeles	45	27.38	0.61
Houston	22.8	19.87	0.87
Oklahoma City	19.4	13.14	0.68
Albuquerque	14	12.93	0.92
Phoenix	16.2	11.55	0.71
Portland	18.1	9.97	0.55
		mean	0.72

- Using Table 5, we can now analyze and plot the relationship between the mean building height and the displacement height. Since there are only 6 cities, this R 2 = 0.76 is considered to be useful as a first approximation. This is needed since there are many cities in the hurricane or typhoon prone areas, which does not have the survey of the displacement height as those shown in Table 5, but the mean building heights in many downtown areas are known as published in the National Building Statistics Database: Version 2 by the Los Alamos National Laboratory (Publication Number LA-UR-08-1921).



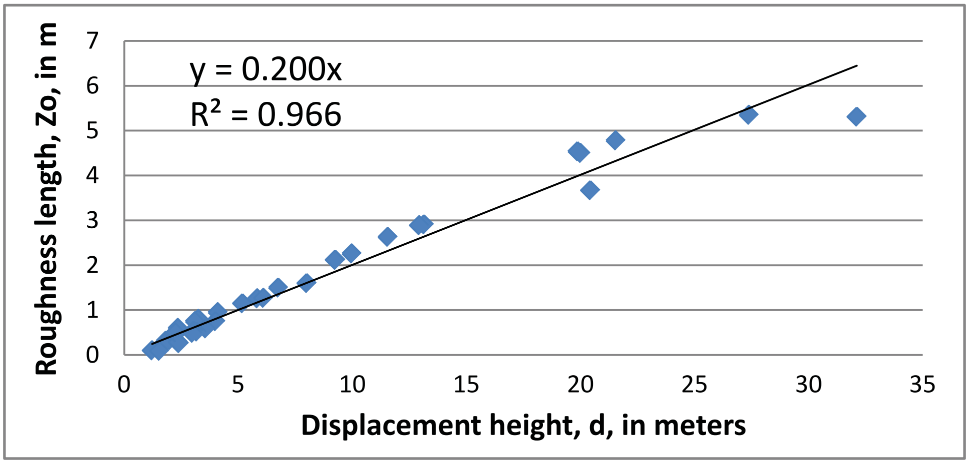
(Data Source : Burian et al., 2005)

Figure 16 : Relationship between mean building height and displacement height

- Because Table 1 requires the value of roughness length, Zo, we further acquire and analyze the datasets including both Zo and the displacement height in more cities. The results are presented in Table 17, which indicates that

$$Zo = 0.2\ d \qquad (8)$$

Since the coefficient of determination, R^2 =0.97, is very high, Eq. (8) should be useful operationally.



(Data Source : Burian et al., 2005)

Figure 17 : Relationship between displacement height and routhness length

VI. An Evaluation using Typhoon Sally in 1996 over Hong Kong and Shenzhen, China

Full-scale monitoring of typhoon effects on super tall buildings was conducted during the passage of Typhoon Sally in 1996 (see Li et al., 2005). For our evaluation, we employ the measurements at Cheung Chau. From the position provided in Li et al (2005), this station is located in Category I. According to Hsu (1988, p. 202), P = 0.10 and Hsu (1988, pp. 126-127), the gradient height = 250 m. These values are in excellent agreement with Category I as listed in Table 1.

Further verification of the gradient height over Hong Kong City is presented in Figures 18 and 19, which show the distinct characteristics of two layer flow with the separation elevation located at 694 m in both wind speed (Fig. 18) and direction (Fig.19). Since the difference between this measured value of 694 m and the proposed value of 650 m is approximate 6 percent, we may use the proposed value as a first approximation.

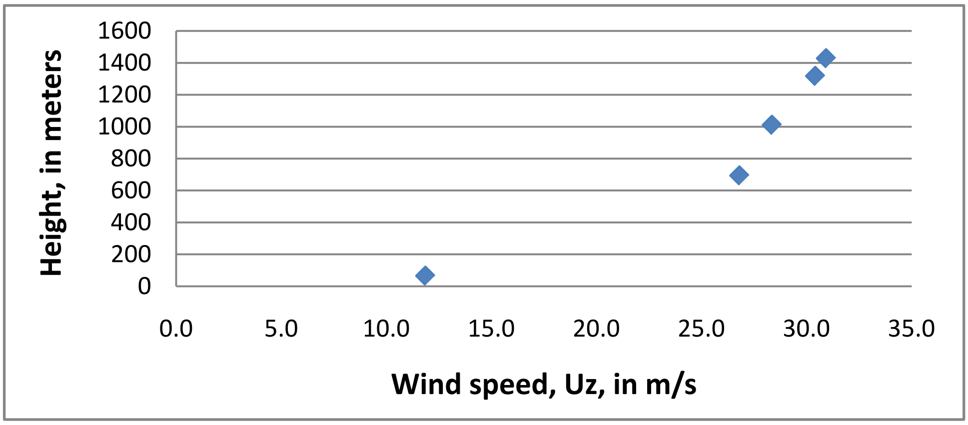


Figure 18 : Variation of wind speed with height at 18Z on 08 September 1996 based on Hong Kong Observatory during Typhoon Sally

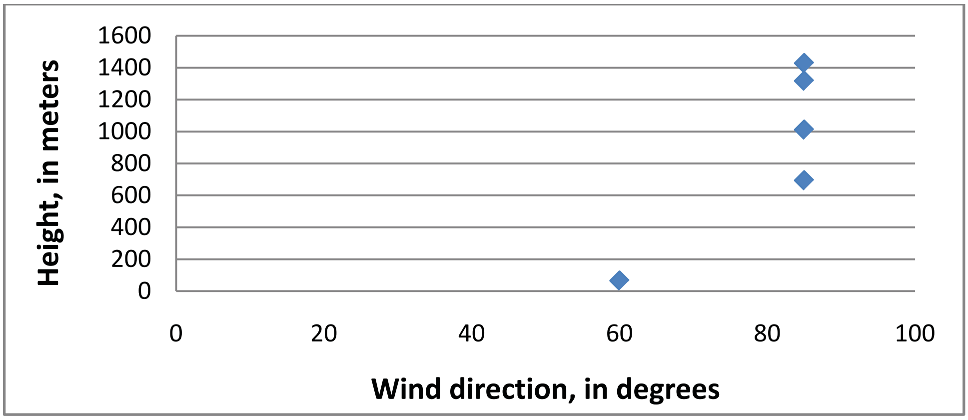


Figure 19 : Variation of wind direction with height at 18Z on 08 September 1996 based on Hong Kong Observatory during Typhoon Sally

With the aforementioned verification of the gradient height in mind, we can now comparethe wind speed measurements atop the tall buildingand the wind speed estimates from Table 1 in Hong Kong.

First, on the basis of the measured max wind speed of 37.5 m/s at 92 m at Cheung Chau, the wind speed at 250 m over that station (Cat. I) is

$$U_{250m} = U_{92m} * (250/92) \text{^}0.103 = 37.5 * 1.11 = 41.6 \text{ m/s}.$$

This max speed is expected to be the same at U650m over Hong Kong and Shenzhen so that the max wind speeds atop of the Central Plaza Tower at 374 m in Hong Kong and Di Wang Tower at 384 m in Shenzhen are estimated from Table 1 for Cat. VI as

$$U_{374m} = U_{650m} * (374/650) \text{ ^ } 0.362 = 41.6 * 0.82 = 34.1 \text{ m/s, and}$$

$$U_{384m} = U_{650m} * (384/650) \text{ ^ } 0.362 = 41.6 * 0.83 = 34.5 \text{ m/s,}$$

respectively. These results are compared with measurements as shown in Table 6.

Table 6 : A comparison of max wind speed between estimated and measured atop tall buildings during Typhoon Sally in 1996

Tall Building	Height, m	Estimated max speed, this study, m/s	Measured, see Li et al (2005), m/s	Difference in percent
Central Plaza Tower in Hong Kong	374	34.1	29.6	13 %
Di Wang Tower in Shenzhen	384	34.5	33.5	3 %

Since the average difference is (0.13 + 0.03)/2 = 0.08 or 8 %, which is within 10 % for the composite margin of error for wind speed measurements, it is reasonable to say that Table 1 is evaluated to be useful operationally.

VII. Conclusions

A proposal based on Choi in 2009 for "unified terrain categories exposures and velocity profiles" has been evaluated extensively in this study. This evaluation includes 3 separate papers published most recently under the conditions of Typhoon Muifa in 2011 over the greater Shanghai, China, region, one study during Hurricane Ike in 2008 over Houston, Texas, USA, one paper for super tall buildings (> 300m) during Typhoon Sally in 1996 over Hong Kong and Shenzhen, China and one study during an atmospheric dispersion experiment in New York City, USA. In addition, in order to support the evaluation of gradient height, upper-air sounding measurements are acquired and analyzed when appropriate. On the basis of these evaluations, it is found that the criteria as shown in Table 1 are useful operationally for engineering applications except the designation of the displacement height which requires further investigation. An alternative approach using the mean building height as the input for the power-law exponent is proposed.

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