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Near-ground wind and its characterization for engineering applications

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Abstract. This report presents the findings of a one-year monitoring effort to empirically characterize and evaluate the nature of near-ground winds for structural engineering purposes. The current wind engineering practice in the United States does not explicitly consider certain important near-ground wind characteristics in typical rough terrain conditions and the possible effect on efficient design of low-rise structures, such as homes and other light-frame buildings that comprise most of the building population. Therefore, near ground wind data was collected for the purpose of comparing actual near-ground wind characteristics to the current U.S. wind engineering practice. The study provides data depicting variability of wind speeds, wind velocity profiles for a major thunderstorm event and a northeaster, and the influence of thunderstorms on annual extreme wind speeds at various heights above ground in a typical rough environment. Data showing the decrease in the power law exponent with increasing wind speed is also presented. It is demonstrated that near-ground wind speeds (i.e., less than 10 m above ground) are likely to be over-estimated in the current design practice by as much as 20 percent which may result in wind load over-estimate of about 50% for low-rise buildings in typical rough terrain. The importance of thunderstorm wind profiles on determination of design wind speeds and building loads (particularly for buildings substantially taller than 10 m) is also discussed. Recommendations are given for possible improvements to the current design practice in the United States with respect to low-rise buildings in rough terrain and for the need to study the impact of thunderstorm gust profile shapes on extreme value wind speed estimates and building loads.

Key words: wind velocity profile; power law; near-ground wind characteristics; wind engineering; extreme value; thunderstorms; shielding; exposure; topographic effects; variability.

1. Introduction

According to insurance records and property damage estimates, high wind conditions account for greater than 80 percent of the economic losses related to catastrophes (NWS 1998). Much of this damage is associated with small buildings, such as homes and other light-frame construction, that

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comprise most of the building population. Therefore, an accurate characterization of near-ground wind conditions is crucial to the efficient design of residential structures to :

(1) adequately resist near-ground winds for the provision of life safety,
(2) provide for a reasonable and predictable frequency of damaging winds that occur in near ground environments, and
(3) address wind related building performance issues in a cost-effective manner.

This paper presents the findings of a one-year monitoring effort to empirically characterize and evaluate the nature of the near-ground winds. The findings are applicable to and compared with the U.S. wind engineering practice for low-rise buildings in rough terrain conditions (i.e., suburban and/ or wooded exposures).

The objective of the research was to monitor near ground winds for a complete annual cycle to obtain information on the following :

(1) the applicability of current wind velocity profile theory (i.e., the power law) in describing the wind conditions near to the ground in typical rough terrain for engineering purposes;
(2) the spatial variability in near ground wind speeds from the perspective of single events as well as annual extremes to assist in the proper treatment of uncertainty in design code formulation (i.e., wind load factor analysis) for small buildings in rough terrain;
(3) the degree of shielding and wind speed-up effects that may randomly occur near to the ground in a typical rough terrain with a mix of trees, low-rise buildings, and open spaces.

In addition to the above objectives, other items of interest were identified during the course of study, such as the change in surface friction (as represented by the power law exponent) as a function of wind speed. Another important issue that arose during the project deals with the affect of thunderstorms on the wind velocity profile and on the estimate of extreme value wind speeds at various heights above ground.

An initial report provided an analysis based on two weeks of wind data and included an extensive literature review of related studies addressing near ground wind in rough terrain and wind velocity profile theories (HUD 1998). This paper expands upon that initial work by including a full year of wind data to evaluate wind characteristics on the basis of annual extremes. The study also looks at two distinctly different wind events – a summer event (i.e., severe thunderstorm) and a winter event (i.e., northeaster) – that were recorded during the one-year monitoring period.

2. Wind monitoring

The wind monitoring effort consisted of five anemometers situated in an industrial park located in Upper Marlboro, Maryland. These stations recorded wind data at a height of about 3.0 m (10 ft) and were placed to represent the near-ground wind field within the developed terrain of the industrial park. A typical near-ground station is shown in Fig. 1. Additional anemometers were located at a central point of the industrial park and attached to an existing communications tower as shown in Fig. 2. These stations were installed at heights of 10 m (33 ft) and 57 m (187 ft) above the ground.

A complete description of the instrumentation and site terrain at each station can be found in a previous report (HUD 1998). The layout of these six stations in the industrial park is shown in the aerial photograph of Fig. 3. (The tower is labeled as station #2.) As seen in the aerial photograph, the surrounding land has small open fields with deciduous trees on the boundaries (eastern direction) and is predominantly characterized by deciduous trees in the other directions. This general terrain

Fig. 1 Portable near-ground wind station with anemometer at a 3 m (10 ft) height above ground

Fig. 2 View of tower with anemometers at 10 m (33 ft) and 57 m (187 ft) heights above ground

condition extends for many kilometers in all directions. Within the industrial park, the buildings are typically about 9.1-m (30-ft) in height. There are also numerous parking lots and several undeveloped lots with trees, brush, and open grassy fields. The terrain is relatively flat with gently rolling hills. These conditions are similar to those found in many residential and commercial developments with a moderate density of structures.

3. Results

3.1. Descriptions of major events, wind profiles, and variability

The Mid-Atlantic region of the United States is subjected to two distinct types of meteorological conditions that typically produce the annual maximum winds: northeasters and thunderstorms. This section of the paper presents and evaluates data from a major event of each type that was experienced during the one-year monitoring period of this study.

Thunderstorms form along the leading edge of an advancing cold front during the summer. The cold front pushes the hot and humid air mass upward, creating brief and intense thunderstorms. These storms (meso-cyclones) are short-lived, localized events and typically last less than one hour. In most of the interior and well inland from the Gulf and Atlantic coasts of the United States, thunderstorms have a predominant influence on design wind speeds. It has been estimated that

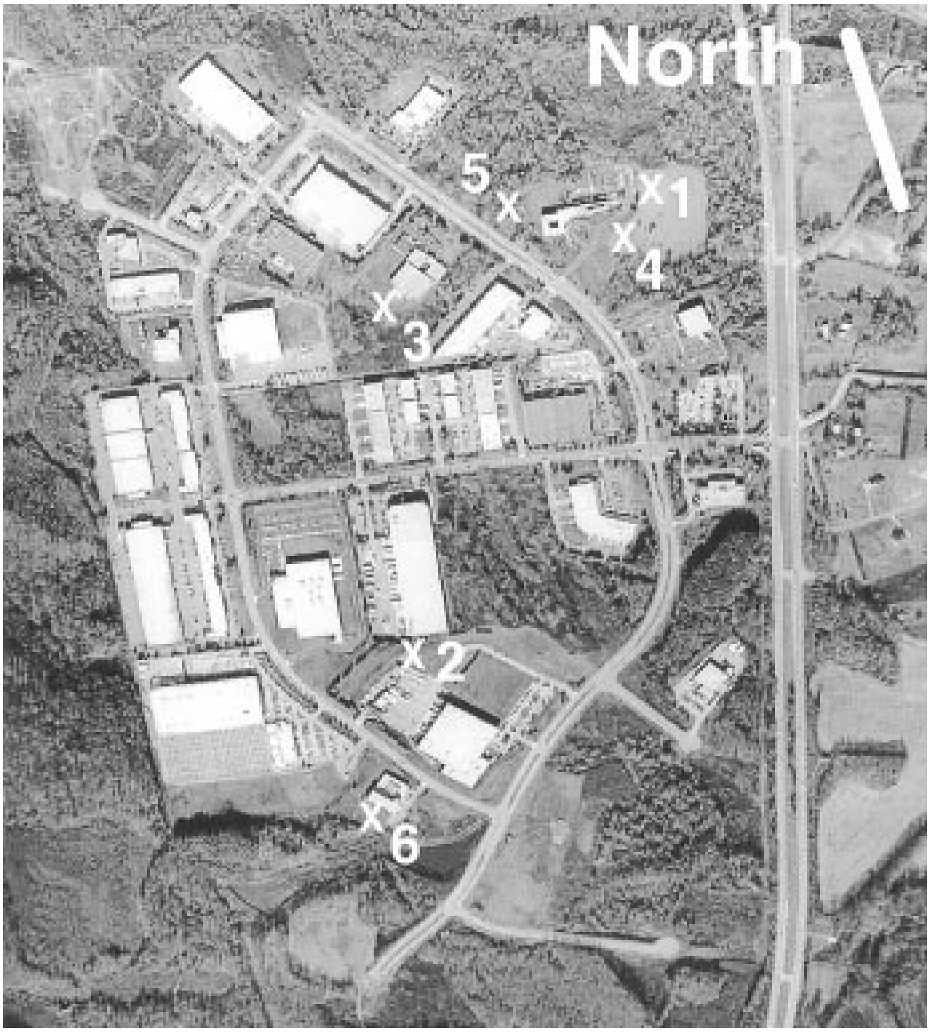

Fig. 3 Aerial photograph of 10 ft (3 m) height wind monitoring stations. The tower station with anemometers at 10 m (33 ft) and 57 m (187 ft) heights is labeled as #2

thunderstorm events account for about one-third of extreme wind speeds recorded in the United States (Thom 1968). However, design wind speeds (i.e., 50-yr mean recurrence interval and greater) in areas along the U.S. Gulf and Atlantic coastline and extending several kilometers inland are predominantly influenced by hurricanes.

The second major wind producer occurs in the winter when a large low pressure system moves up the Atlantic coast. This storm system produces continuously strong winds that can last for several days or longer. These large cyclonic weather systems are known as "nor'easters" because of the predominate northeasterly winds produced ahead of the storm. This type of event is particularly noted for its impact on coastal erosion. As mentioned, design wind speeds along the Atlantic coast are predominantly influenced by hurricanes.

3.1.1. Peak winter event (Northeaster)

Table 1 presents the data obtained from the most intense winter storm event experienced for the one-year period of record which was a Northeaster that occurred on January 3, 1999.

The gust wind velocity profile for the large cyclonic storm (winter event) closely follows the shape of a typical power law wind speed profile model (Fig. 4). The derivation and application of the power-law wind speed profile and the gust factor is adequately covered in the literature (Durst 1960, Simiu and Scanlan 1996, HUD 1998, ASCE 1999). It should be noted that the power law profile was originally intended to be applied to mean wind speeds for large-scale cyclonic winds based on wind speed measurements dating as far back as 1885 (as reported by Pagon 1935, Davenport 1960 and HUD 1998).

In Fig. 4, The power law trend shows an R-square of 0.98 and closely conforms to the measurements at 3-m (10-ft), 10-m (33-ft), and 57-m (187-ft) for the northeaster event. Using the 10 m and 57 m measurements, the power law fits these two data exactly using an α value of 6.2 for the exponent ($1/\alpha$) of the power law and a gradient height of 41-m (1,350-ft). The gradient wind speed

Table 1 Peak winter wind event[1]

Recording Interval	Station	Time	Maximum Gust (m/s)	Gust Time	Gust Direction	Mean Speed (m/s)	Gust Factor	Std. Dev. (m/s)	Turbulence Intensity	Mean Direction
1 min.	1	438	13.9	437	S	8.3	1.68	2.1	0.251	E
	3	516	13.4	515	S	7.5	1.79	2.4	0.326	S
	4	601	13.8	600	SW	10.1	1.36	1.9	0.187	SW
	5	600	9.8	559	S	5.1	1.90	1.8	0.356	S
	6	450	13.1	449	S	7.9	1.67	2.0	0.259	S
	10 m	518	20.5	517	S	13.7	1.50	2.8	0.202	SE
	57 m	539	24.0	538	SE	18.3	1.31	3.3	0.181	SE
10 min.	1	540	13.1	539	S	6.0	2.17	2.1	0.342	N
	3	520	15.9	511	S	6.0	2.63	2.3	0.375	S
	4	610	14.6	601	SW	6.1	2.38	2.5	0.410	SW
	5	520	11.4	519	SE	3.7	3.10	1.7	0.461	SE
	6	520	15.5	515	S	6.2	2.49	2.1	0.341	S
	10 m	540	18.4	538	SE	10.5	1.75	2.6	0.248	SE
	57 m	540	24.0	538	SE	14.3	1.68	3.6	0.256	SE
3 sec	1	600	15.5	550	S					
	3	600	15.9	511	NE					
	4	600	15.8	559	SW					
	5	600	11.4	519	SE					
	6	600	18.2	525	S					
	10 m	600	20.5	517	S					
	57 m	500	27.1	442	SE					

1 mph = 0.447 m/s, 1 ft = 0.305 m

[1]Maximum gust speed, maximum mean wind speed, gust factor, and turbulence intensity are reported for the averaging time interval in the left-most column. The gust factor is the ratio of the maximum gust in the time interval to the mean wind speed for the averaging time interval. The turbulence intensity is the standard deviation of gust wind speed measurements taken at 1 second intervals divided by the mean wind speed for the averaging time interval.

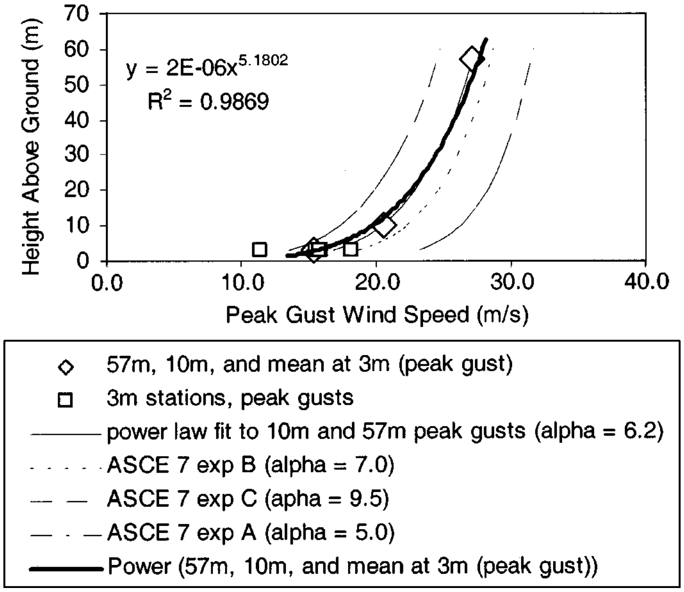

Fig. 4 Application of the Power Law to peak gust wind speeds recorded during Northeaster wind event on January 3, 1999

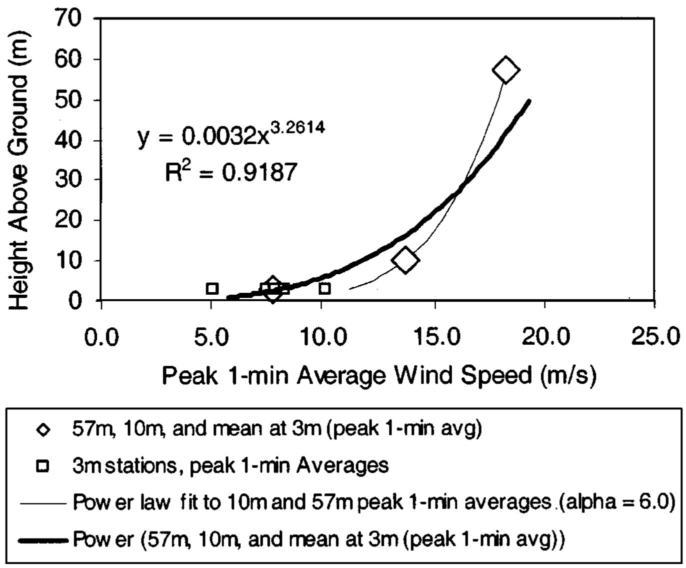

Fig. 5 Application of the power law to peak 1-minute average wind speeds recorded during Northeaster wind event on January 3, 1999

is estimated to be 37.2 m/s based on that representation of the wind velocity profile. For comparison, the peak gust gradient wind speed for the event is used to construct wind velocity profiles for various terrain conditions as defined in ASCE 7-98 (ASCE 1999) for city centers (exposure A), suburban/wooded terrain (exposure B), and open, flat grassy terrain (exposure C). It is notable that

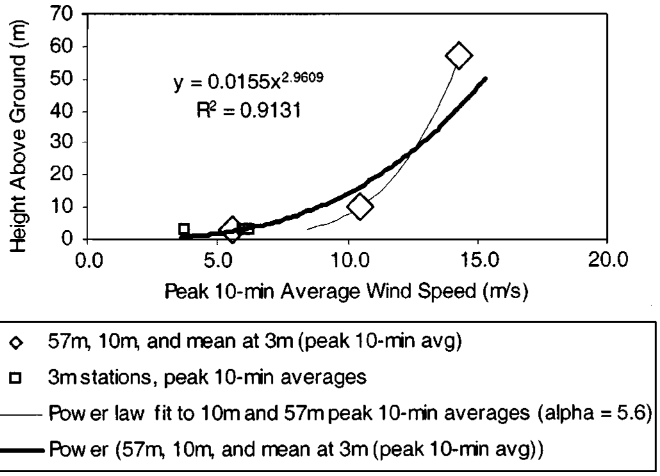

Fig. 6 Application of the power law to peak 10-minute average wind speeds recorded during Northeaster wind event on January 3, 1999

the power law theory appears to predict peak gust wind speeds very well, and with only slight over-prediction, at heights as low as 3-m (10-ft) in rough terrain (i.e., below the displacement height). It is interesting that the power law theory appears to become progressively more conservative in predicting near ground wind speeds as the wind speed averaging time increases (see Figs. 5 and 6).

Based on the assumption of a normality, the 5th-percentile and 95th-percentile estimates of the 3-m station peak gust wind speeds (Table 1) are 11.3 m/s and 19.4 m/s, respectively. The corresponding 5th- and 95th-percentile a values (based on the 5th- and 95th-percentile wind speeds and a power law trend fit to the lower portion of the wind profile) is estimated at 3.2 and 8, respectively. The lower wind speed at the 3-m height (which precipitated the lower-percentile estimate of the 3-m wind speed and the corresponding α value) is associated with station 5 which experienced significant shielding and reduced wind speeds from surrounding trees in the upwind direction (see Fig. 3). The higher α value is associated with station 6 which may have experienced localized wind speed-up effects from channeling or vortexing due to its proximity to an upwind building (see Fig. 3). As shown in Table 1, this effect disappears for the 1-minute and 10-minute wind speed averaging times at monitoring station 6.

The development of wind load factors for use in U.S. wind engineering standards and codes assumes that the wind velocity profile represents the mean gust wind speed temporally, spatially, and in terms of annual extremes (ASCE 1999, Ellingwood and Tekie 1998). (The issue of annual extremes and its relevance to the near-ground wind speed profile is discussed later). Thus, the wind load factor is premised on the use of a “mean” gust wind speed condition and accounts for the sources of variability through assignment of an uncertainty to the wind velocity pressure exposure coefficient, K_z, which is derived from the power law. This assignment of uncertainty is largely based on expert opinion rather than empirical evidence (Ellingwood and Tekie 1998). Therefore, the wind speed variability as reported above for near-ground heights provides needed information for the purpose of wind design code development and verification, particularly with respect to the treatment of uncertainty and biases in the determination of a wind load factor to be applied to code-nominal wind loads.

It is interesting to note that the wind load factor in ASCE 7-98 (ASCE 1999) is based on a coefficient of variation (COV) of approximately 0.19 assigned to K_z under the assumption of normality (Ellingwood and Tekie 1998). The corresponding COV for α is 0.19. This COV was intended for exposure *B* terrain and a height above ground of 6 m (20 ft). A COV of 0.12 to 0.14 was hypothesized for exposure *C* terrain, also by expert opinion.

Based on the variability of near ground gust wind speed data of this study, the COV of α appears to be approximately 0.23 for a height of 3 m (10 ft). Since the variability in wind speed tends to decrease with height, the estimated COV of 0.19 for α appears to be reasonable in an exposure *B* setting at a height of 6 m (20 ft). However, the treatment of uncertainty in developing a wind load factor for ASCE 7-98 assumes (also by a survey of expert opinion) that the code-nominal value of α essentially represents the actual mean gust wind velocity profile (i.e., an absence of significant bias in the code nominal values of K_z that are based on the power law profile) (Ellingwood and Tekie 1998).

The data of this study (Fig. 4 and Table 1) indicates that the power law profile (when fixed to a gradient wind speed as done in ASCE 7-98), produces a significant conservative bias in design wind loads below the standard 10 m (33 ft) height in rough terrain. For example, the over-prediction bias may be as much as 10 percent in terms of wind speed (20% in terms of load) at the 3-m height. This bias is in addition to the bias that is created by the code practice of discretizing exposure conditions. For example, the typical rough terrain condition of this study shows that use of the exposure *B* condition of ASCE 7-98 would result in a 22 percent over-estimate of wind speed or nearly a 50 percent over-estimate of wind load at the 3-m height. Thus, a reasonable mean-to-nominal ratio of K_z may be as low as 0.67 instead of 1.0 in the below 10 m (33 ft) range in rough terrain. This situation demonstrates the tendency for a significant over-prediction of wind loads (and a compounding over-prediction of the wind load factor) for relatively small buildings in typical rough terrain when using ASCE 7-98 exposure *B* conditions. With new exposure definitions being considered for updating of ASCE 7-98 that prescribe open area limitations within the exposure *B* category, the study site may actually be classified as exposure *C* in future editions of this design standard. In such a case, the near ground design wind speeds for the study site could be over-estimated by 50 percent which gives an over-estimate of 125 percent in terms of wind load for relatively small buildings that are less than 10 m (33 ft) in height. The situation is yet compounded further if the tendency of designers to specify a more conservative exposure category is also considered (Ellingwood and Tekie 1998).

Such discrepancies between design practice and actual conditions may partially explain why an engineering evaluation of small buildings, such as homes, often results in conclusions that conflict with actual performance experience. Other studies have been recently conducted to carefully and scientifically evaluate actual housing performance in hurricanes and earthquakes to identify statistically valid cause-and-effect relationships between construction characteristics and damage frequencies and to improve both the design theory and construction practice used for homes in the United States (HUD 1993, HUD 1994, NAHB Research Center 1995, HUD 1999a, HUD 1999b).

3.1.2. Summer event (Thunderstorm)

Table 2 presents the data obtained from the most intense thunderstorm event which occurred during the one-year monitoring period on July 21, 1998.

The meso-cyclone (summer event) profile shows a backward bend due to the 10 m (33 ft) wind speed being slightly greater than the wind speed at the higher elevation of 57 m (187 ft) above the ground surface (Fig. 7). The data in this study demonstrates that the wind speed at the 10 m (33 ft) elevation can closely coincide with the peak of a thunderstorm wind velocity profile. It is also

Table 2 Peak summer wind event[1]

Averaging Time Interval	Station	Time	Maximum Gust (m/s)	Gust Time	Gust Direction	Mean Speed (m/s)	Gust Factor	Std. Dev. (m/s)	Turbu-lence Intensity	Mean Direction
1 min.	1	1815	14.7	1814	NW	10.2	1.43	2.0	0.197	W
	3	1813	10.4	1812	W	4.5	2.30	2.9	0.638	SW
	4	1811	21.8	1810	W	14.5	1.50	3.5	0.240	W
	5	1812	7.5	1811	W	4.2	1.77	1.7	0.408	W
	6	1738	4.7	1737	S	3.9	1.20	0.5	0.124	SW
	10 m	1814	29.7	1813	NW	15.3	1.94	7.3	0.475	NW
	57 m	1814	26.6	1813	NW	22.7	1.18	3.1	0.139	NW
10 min.	1	1820	14.7	1812	W	7.0	2.11	2.9	0.415	W
	3	1820	10.4	1812	W	2.3	4.53	1.8	0.780	S
	4	1820	21.8	1810	W	8.0	2.70	3.5	0.439	W
	5	1820	8.2	1813	W	2.5	3.21	1.6	0.630	W
	6	1700	5.0	1659	SW	3.4	1.47	1.0	0.298	SW
	10 m	1820	29.7	1813	NW	7.5	3.95	5.0	0.660	NW
	57 m	1820	26.6	1813	NW	11.6	2.30	5.7	0.494	W
Gust (1-3sec)	1	1900	14.7	1812	W					
	3	1900	10.4	1812	NE					
	4	1900	21.8	1810	W					
	5	1900	8.2	1813	W					
	6	1900	10.4	1812	N					
	10 m	1900	29.7	1813	NW					
	57 m	1900	26.6	1813	NW					

1 mph = 0.447 m/s, 1 ft = 0.305 m

[1] Maximum gust speed, maximum mean wind speed, gust factor, and turbulence intensity are reported for the averaging time interval in the left-most column. The gust factor is the ratio of the maximum gust in the time interval to the mean wind speed for the averaging time interval. The turbulence intensity is the standard deviation of gust wind speed measurements taken at 1 second intervals divided by the mean wind speed for the averaging time interval.

apparent that use of power law wind profile theory may be grossly inadequate in regions that have design wind speeds predominantly influenced by thunderstorms. This issue is addressed later in the context of the annual extreme value peak gust wind velocity profile. It is noted that the actual thunderstorm event wind profile could be somewhat different in shape due to the limited number of data points (3) defining the shape in Fig. 7 using simple curve smoothing. It should also be noted that the backward bending profile shape does not exist for wind speed averaging times of 1-minute and 10-minutes (see Table 2).

The above finding does not appear to agree with one prior study on thunderstorm gust fronts where it is suggested that the power law or log law adequately represents the gust front of a passing thunderstorm for the heights up to 100 m and that, for heights above 100 m, the variation in wind speed with height is negligible (Sinclair Anthes and Panofsky 1973 as reported in Simiu and Scanlan 1996). Instead, this study indicates that the power law is inadequate for heights below 100 m since the data approximates a flat profile shape for heights between 10 m and 57 m in rough terrain conditions. In fact, a power law wind velocity profile based on the peak gust wind speed at the

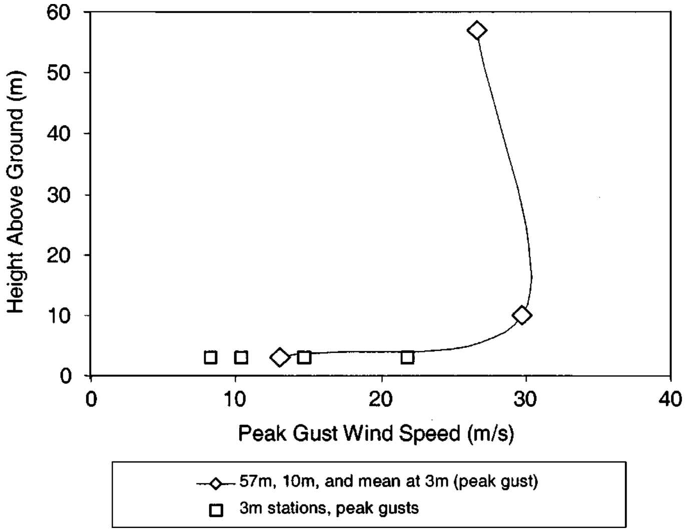

Fig. 7 Estimated profile shape of the summer maximum event (peak gust) based on the 57 m (187 ft) tower anemometer, the 10 m (33 ft) tower anemometer and the average of the five 3 m (10 ft) anemometer stations. 1 ft = 0.305 m, 1 mph = 0.447 m/s

10 m (33 ft) height could result in significant over-estimation of wind speeds above and below this standard height which is used to develop the design wind map for use in the United States.

Another significant issue based on the above thunderstorm profile shape relates to the treatment of the wind velocity profile shape in developing wind design load parameters based on conventional boundary layer wind tunnel practices. To thoroughly address the implication of this issue, a thorough study of wind climate data would also be necessary to ascertain the frequency of such events, variations in the wind velocity profile shape, and the impact on estimates of design wind speeds. Since thunderstorms are known to produce design wind speeds in many areas of the United States, the significance and need for such a study cannot be overstated and has been recognized by others (Simiu and Scanlan 1996).

3.2. Variation in power law exponent as a function of wind speed and season

Several individual wind events that produced relatively high wind speeds over the period of record were extracted from the data to evaluate the relationship between the denominator, α, of the power law exponent, $1/\alpha$, and the magnitude of wind speed. Individual wind events were selected based on a 24-hour period ranging from midnight to midnight. As seen in Fig. 8 through 10 the estimated value of α varied inversely with the magnitude of wind speed. This trend is most evident for the 1-minute and 10-minute mean wind speeds. At the lower wind speeds (e.g., less than 8.9 m/s (20 mph)), this effect is amplified by convective (i.e., thermal) effects; however, at higher wind speeds the continuing decrease is attributed to surface friction having a dependence on magnitude of wind velocity. As wind speeds increase further, the rate of change of the exponent appears to decrease and stabilize to a more constant rate where it is governed primarily by increased surface friction as a result of the kinematic viscosity of the faster moving, well mixed (i.e., neutral stability) air. A linear regression analysis was performed on the data to give an indication of the trend of α as a function of wind speed. It is likely that the best fit would be a curve asymptotic to a minimum α.

More data at higher wind speeds is needed to provide greater insight into the rate of change of α at higher (i.e., design level) wind conditions for peak gust wind speeds. This apparent trend in the reduction of α with increasing wind speed is important for determining surface roughness effects on design gust wind speeds that are typically greater than 38 m/s (85 mph) in the United States. Not considering this effect in defining exposure conditions may lead to an additional conservative bias in the wind engineering practice.

There is an increased data scatter associated with the peak gust data so additional monitoring is desirable to quantify the relationship of α to wind velocities of greater magnitude. However, the trend is very evident.

Although not reported here, the data also appeared to show a seasonal effect on the estimated power law exponent due to the presence or absence of foliation on the deciduous trees that populated the surrounding terrain and were used throughout the industrial park for landscaping. The denominator of power law exponent, α, tended to be smaller in the summer months than in the

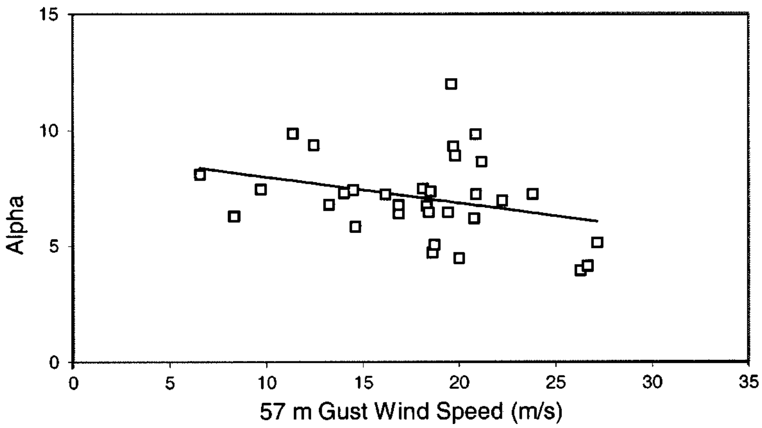

Fig. 8 Plot of estimated α for daily peak gust wind measurements based on 57 m (187 ft) tower anemometer and the average of five 3 m (10 ft) anemometer stations. 1 ft = 0.305 m, 1 mph = 0.447 m/s

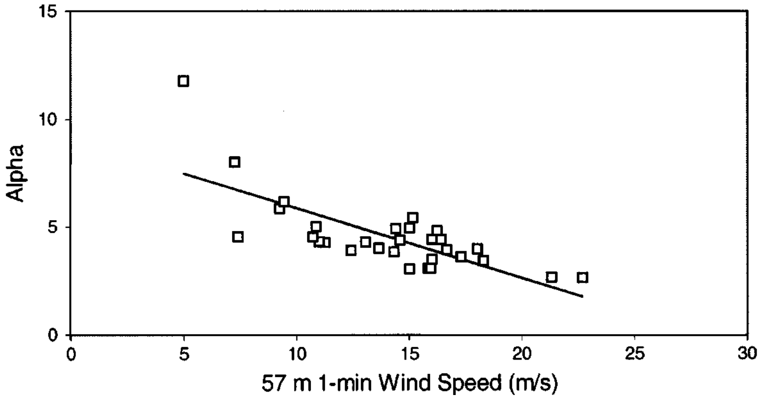

Fig. 9 Plot of estimated α for daily maximum 1-minute wind measurements based on 57 m (187 ft) tower anemometer and the average of five 3 m (10 ft) anemometer stations. 1 ft = 0.305 m, 1 mph = 0.447 m/s

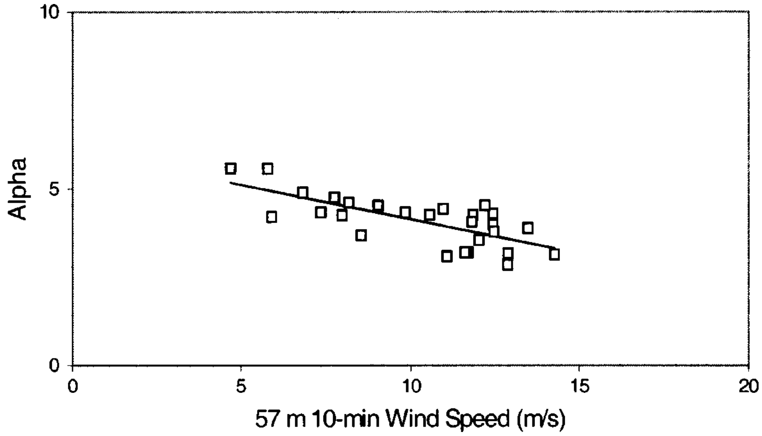

Fig. 10 Plot of estimated α for daily maximum 10-minute mean wind measurements based on 57 m (187 ft) tower anemometer and the average of five 3 m (10 ft) anemometer stations. 1 ft = 0.305 m, 1 mph = 0.447 m/s

winter months. This finding may be particularly significant in areas that have design wind speeds typically associated with summer events, provided the design event is not of sufficient duration and magnitude to substantially defoliate the trees, which would be expected in a major hurricane near land-fall.

3.3. Annual extreme value wind speeds

This section examines the near ground wind data collected from March 19, 1998 through March 18, 1999 for the purpose of investigating variation in annual extreme values of wind speed in a rough, near-ground environment. Key annual extreme wind speed data for each station is summarized in Table 3 including the following information:

· annual extreme wind speeds for each anemometer (peak gust and 1-minute and 10-minute means),
· wind direction at annual extreme gust and mean wind speeds (also included is a time code as follows: year/julian day/hour:minute:second), and
· mean and COV of wind speed for the five 3-m (10-ft) height stations.

In Table 3, it is shown that the coefficient of variation (COV) in annual extreme peak gust wind speed at the 10 ft (3 m) elevation is 0.20. The COV for the 1-minute annual extreme wind speeds was slightly higher. The relatively high annual extreme gust wind speed for the 3-m near-ground station 4 is attributed to a topographic effect (a 6-m (20-ft) knoll) particularly sensitive to the specific wind direction associated with the annual extreme gust of record. Conversely, the consistently low annual extreme gust wind speed value for station 5 is attributed to shielding provided by a nearby building and, more importantly, surrounding trees. It was also in a slight depression in the local topography.

A plot of the annual extreme value wind speeds at the measured locations as well as the two major wind events addressed earlier are shown in Fig. 11. The annual extreme value wind speed variation with height above ground for the one-year period of record is essentially defined by the thunderstorm event. However, it should be noted that the backward bending shape of the profile

Table 3 Annual extreme wind speeds by station and averaging time interval

Station	Gust Wind Speed (m/s)	1-min Mean Wind Speed (m/s)	10-min Mean Wind Speed (m/s)
1	17.1 (S) 99/63/09:03:21	10.2 (W) 98/202/18:15	7.3 (S) 99/63/11:30
3	16.4 (NW) 99/65/23:52:46	9.5 (NW) 99/43/17:36	7.1 (NW) 99/43/16:40
4	21.8 (W) 98/202/18:10:17	14.5 (W) 98/202/18:11	8.6 (W) 99/63/08:50
5	12.2 (NW) 99/43/16:32:12	7.6 (W) 99/43/16:33	5.5 (W) 99/63/16:10
6	18.2 (S) 99/3/05:25:32	11.0 (NW) 98/364/09:06	7.0 (NW) 99/35/22:50
10 ft Mean	17.1	10.5	7.1
10 ft COV	0.20	0.24	0.16
2 (33 ft)	29.7 (NW) 98/202/18:13:37	15.3 (NW) 98/202/18:14	10.5 (SE) 99/3/05:40
2 (187 ft)	27.1 (SE) 99/3/04:42:01	22.7 (NW) 98/202/18:14	14.3 (SE) 99/3/05:40

1 ft = 0.305 m, 1 mph = 0.447 m/s
[1] Based on the mean of the annual extreme α for each of the five 10-ft (3-m) stations.
Values in parenthesis are based on the mean wind speed of the five 10-ft (3-m) stations.

disappears at longer wind speed averaging times (see Table 3). This effect is due to the short-lived nature of the fast-moving gust front in the thunderstorm event.

Based on a gradient height of 411 m and an α value of 6.2 as determined earlier for the site based on the northeaster event and calibrating to the 10-m (33-ft) tower anemometer's annual extreme gust reading, the power law fit to data is shown in Fig. 11 along with data points showing the annual extreme values at other stations and heights. This approach represents current wind engineering practice in the United States (ASCE 1999) where design wind speeds are based on a 10 m (33 ft) height. It further demonstrates the possible conservative error in determining design wind speeds at other heights when extreme value gust wind speeds at the standard 10 m (33 ft) height are governed by thunderstorm events that exhibit a flat or backward-bending profile shape.

The power law theory provides a reasonable fit only in the range of 4.6 m (15 ft) to 13.7 m (40 ft) to the annual extreme value wind velocity profile as defined in this study for one given year of data. The over-estimate of the actual extreme value wind speeds at elevations outside of this range can be greater than 40 percent at heights of 57 m (187 ft) and 3 m (10 ft). This condition corresponds to a conservative estimate of velocity pressure at a particular elevation (i.e., design wind load) by as much as a factor of 2. This effect compounds the problems with wind speed over-estimation in near-ground rough terrain conditions as discussed earlier in relation to the northeaster wind event.

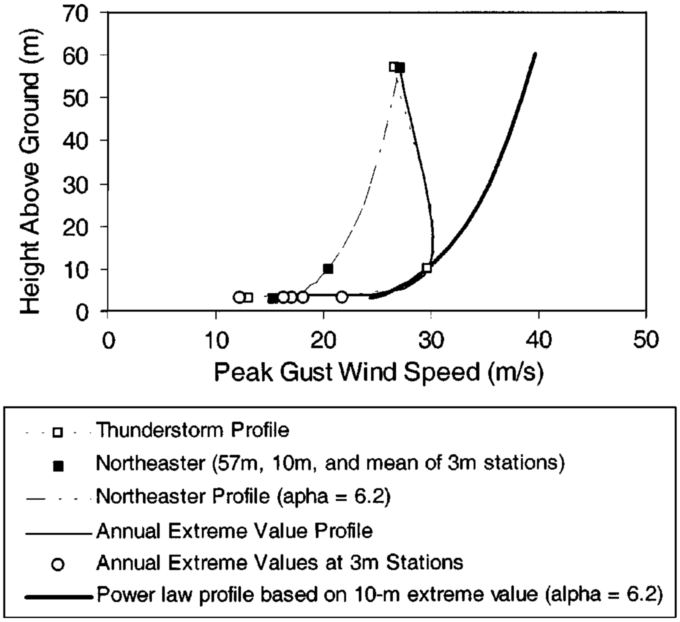

Fig. 11 Comparison of actual summer event, winter event, and annual extreme peak gust wind profiles to a Power Law profile ($\alpha = 6.2$) calibrated to the annual extreme wind speed at an elevation of 10 m (33 ft). 1 ft = 0.305 m, 1 mph = 0.447 m/s

Building wind loads have been developed on the basis of applying conventional boundary layer wind flow, which does not reflect wind velocity profile shapes or wind speed variation that may occur in events such as thunderstorms or in thunderstorm-prone wind climates. Thus, the determination of building wind loads may depart significantly (to the conservative) from actual wind loads as indicated by the findings of this study. Because the power law was never intended to apply to thunderstorm profiles as shown in Fig. 11, the above observation is not intended to be a criticism of the power law (or similar profiles), but rather a constructive criticism of the nature of its application in current wind engineering practice in the United States. This concern is particularly relevant to the design of buildings that are substantially taller than the standard 10 m (33 ft) anemometer height and that are located in thunderstorm-prone wind climates.

Interestingly, the 57 m (187 ft) peak gust wind speeds for the summer and winter events are remarkably close, less than a 2% difference (0.49 m/s (1.1 mph)). This similarity of characteristics

Table 4 Comparison of near-ground wind characteristics

	Summer event	Winter event
57-m wind speed, m/s	26.6	27.1
3-m mean wind speed, m/s	13.1	15.3
3-m standard deviation, m/s[1]	5.4	2.5
3-m COV[1]	0.412	0.162

1 ft = 0.305 m, 1 mph = 0.447 m/s

[1]The standard deviation and COV are for the five 3-m (10-ft) near ground wind station measurements.

does not carry through to the measured wind at the 3 m (10 ft) stations as shown in Table 4.

This data shows that the summer event had a lower average wind speed and greater variability for the five 3 m (10 ft) stations. The variability may be influenced by several factors including:

· localized downdrafts associated with meso-cyclonic events (shown by the higher wind speed recorded at the 10 m (33 ft) elevation when compared to the 57 m (187 ft) elevation),
· greater turbulence generally realized near to the ground, and
· differences in shielding from ground vegetation during winter and summer events (i.e., trees had leaves during the summer event but not during the winter event).

4. Conclusions

The following conclusions are supported by this study :

1. The wind speed profile in a typical rough terrain exposure was characterized for two unique wind events and on the basis of annual extremes.
2. The power law wind profile theory was found to fit the gust velocity profile in rough terrain very well down to a height of 3 m for a large-scale cyclonic event (northeaster). The fit became progressively worse as the wind averaging time was increased.
3. The variability of near ground wind speed in rough terrain was found to agree reasonably well with assumptions regarding uncertainty used to determine the wind load factor in ASCE 7-98.
4. The mean-to-nominal ratio of the code-assumed gust velocity profile relative to the actual mean gust velocity profile was found to be 0.67 instead of 1.0 as assumed in the development of the wind load factor for ASCE 7-98. This result applies to near ground wind speeds in rough terrain and indicates the presence of a significant over-design bias (i.e., 50% load over-estimate) for low-rise buildings located in such terrain when designed using ASCE 7-98.
5. Thunderstorm events can produce a marked backward bending profile shape that can significantly influence the annual extreme value wind velocity profile shape.
6. As much as a 40% over-estimate of wind speeds above and below the standard 10-m anemometer height can occur if the 10-m annual extreme value wind speed represents the peak gust of the thunderstorm front as occurred in this study. As a result, building wind loads may be significantly over-estimated based on design wind speeds normalized to a 10 m (33 ft) height and the assumption of the power law (or similar) profile shape. The magnitude of over-estimation depends on the influence of thunderstorms on design wind speed characterizations in thunderstorm-prone wind climates.
7. The denominator, α, of the power law exponent, $1/\alpha$, varies inversely with wind speed magnitude and appears to be asymptotic at higher wind speeds to a lower value.
8. The findings help to shed some light on why certain types of buildings appear to have a greater life expectancy with respect to wind than determined using current engineering practice.

Recommendations

The following recommendations are provided based on the findings of this study :

1. A wind profile characterization approximately representing the surface roughness conditions of the study site is needed in ASCE 7-98 to minimize the over-design bias relative to typical design conditions seen by many low-rise buildings. The profile should be between Exposures

A and B as defined in ASCE 7-98 and apply to wooded and moderately developed terrain with small open areas. At the same token, the actual surface roughness in Exposure B should be more accurately described from a visual perspective to improve the accuracy of the design code application.

2. The wind load factor used in ASCE 7-98 should be re-evaluated in consideration of the large conservative bias in mean-to-nominal wind profile estimates as identified in this study for rough, near-ground wind conditions.
3. The impact of variations in the wind velocity profile shape due to the influence of thunderstorm events on design wind speeds and building wind loads should be seriously considered for further study. This consideration is necessary to obtain efficient wind load design provisions for different types of structures.

References

ASCE (1999), *Minimum Design Loads for Buildings and Other Structures (ASCE 7-98)*, American Society of Civil Engineers, Reston, VA.

Davenport, A.G. (1960), *Wind Loads on Structures*, Technical Paper No. 88 of the Division of Building Research, National Research Council, Ottawa, Canada.

Durst, C.S. (1960), "Wind speeds over short periods of time", *Meteor. Mag.*, **89**, 181-187.

Ellingwood, B.R. and Tekie, P.B. (1998). *Wind Load Statistics for Probability-Based Structural Design*, prepared by Johns Hopkins University (Baltimore, MD) for the National Association of Home Builders and the U.S. Department of Housing and Urban Development, Office of Policy Development and Research, Washington, D.C.

HUD (1993), *Assessment of Damage to Single-Family Homes Caused by Hurricanes Andrew and Iniki*, prepared by the NAHB Research Center, Inc. for the U.S. Department of Housing and Urban Development, Office of Policy Development and Research, Washington, D.C.

HUD (1994), *Assessment of Damage to Residential Buildings Caused by the Northridge Earthquake*, prepared by the NAHB Research Center, Inc. for the U.S. Department of Housing and Urban Development, Office of Policy Development and Research, Washington, D.C.

HUD (1998), *Monitoring of Near Ground Wind in a Built-up Suburban Environment*, U. S. Department of Housing and Urban Development, Office of Policy Development and Research, Washington, D.C.

HUD (1999a), *Reliability of Conventional Residential Construction: An Assessment of Roof Component Performance in Hurricane Andrew and Typical Wind Regions of the United States*, prepared by the NAHB Research Center, Inc. for the U.S. Department of Housing and Urban Development, Office of Policy Development and Research, Washington, D.C.

HUD (1999b), *Evaluation of Housing Performance and Seismic Design Implications in the Northridge Earthquake*, prepared for the U.S. Department of Housing and Urban Develoment, Office of Policy Development and Research, Washington, D. C.

NAHB Research Center (1996), *Assessment of Damage to Homes Caused by Hurricane Opal*, perpared for the Florida State Home Builder's Association by the NAHB Research Center, Inc., Upper Marlboro, MD.

NWS (1998), *Summary of U.S. Natural Hazard Statistics and Storm Data.* National Weather Service, Office of Meteorology and the National Climate Data Center, Asheville, NC. www.nws.noaa.gov/om/hazstats.htm

Pagon, W.W. (1935), "Wind velocity in relation to height above ground", Engineer's News Record, May 23, 1935.

Simiu, E. and Scanlan, R.H. (1996), *Wind Effects on Structures - Fundamentals and Applications to Design*, John Wiley & Sons, Inc., New York, NY.

Sinclair, R.W., Anthes, R.A. and Panofsky, H.A. (1973), Variation of the low level winds during the passing of a thunderstorm gust front, NASA Contractor Report No. CR-2289.

Thom, H.C.S. (1968), "New distributions of extreme wind speeds in the United States", *J. Struct. Div., ASCE,* No. ST7, Proc Paper 6038 (July 1968), 1787-1801.

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