Technical Note

Planetary Boundary Layer Modeling and Standard Provisions for Supertall Building Design

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Abstract: According to recent results of planetary boundary layer research relevant to the design of tall buildings subjected to large-scale synoptic storm winds, for elevations of up to at least 1 km, the longitudinal mean wind speeds are monotonically increasing with height. It is shown that, for this reason, to avoid the possible unconservative design of supertall buildings significantly affected aerodynamically by neighboring buildings, an explicit derogation from the ASCE 7 standard specification of the gradient heights z_g is necessary for buildings with heights greater than z_g. **DOI: 10.1061/(ASCE)ST.1943-541X.0001804.**

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Introduction

In the *Canadian Structural Design Manual* (National Research Council 1971), the *AIJ Recommendations for Loads on Buildings* (Architectural Institute of Japan 2004), and ASCE 7-10 (ASCE 2010), the wind speeds in the planetary boundary layer (PBL) are modeled for structural engineering purposes by strictly empirical power laws developed essentially in the 1960s or earlier. In these models, wind speeds increase monotonically within the boundary layer up to the gradient height z_g (a term applied in the standard to both cyclostrophic and geostrophic conditions), specified to be 200–250 m for water surface exposure, 300–350 m for open terrain exposure, and 400–450 m for suburban terrain exposure; for elevations $z \geq z_g$, the wind speed is assumed to be constant and equal to the gradient speed. Fundamentally, these models are based on the following assertions—now largely obsolete—pertaining to large-scale storms (Davenport 1965, p. 61): (1) the logarithmic law is valid up to a height of 30–90 m; (2) the power law is valid up to the gradient height, above which the mean velocity no longer increases with height; (3) the gradient height is generally of the order of 300–600 m; and (4) the influence of the isobars' curvature on the wind profile "is only significant for small radii of curvature" and can be neglected "under most circumstances."

This paper is concerned with large-scale synoptic storms, to which the term planetary boundary layer or, equivalently, atmospheric boundary layer—with no further qualifications—is typically applied in the meteorological literature. The standards and codes cited earlier do not differentiate between large-scale synoptic storms and other storms, including thunderstorms and tropical cyclones. Partly because the duration of the highest winds is significantly shorter for thunderstorms than for large-scale synoptic storms (Simiu and Scanlan 1986, p. 80) and, in the authors' opinion, primarily because not enough research on thunderstorm wind characteristics has been performed to date, it is tacitly assumed in ASCE 7-10 that specifications applicable to large-scale synoptic storms adequately cover thunderstorms as well. Also, preliminary research (Simiu et al. 1976; Nash 1969) suggests that a similar assumption is acceptable for tropical cyclone winds. According to measurements reported, e.g., by Powell et al. (2003), hurricane wind speeds over surfaces with open water exposure increase in accordance with the logarithmic law up to 300–400 m elevation, above which they tend to decrease.

Planetary boundary layer (PBL) research was conducted in the 1960s and 1970s by using asymptotic methods (Csanady 1967; Blackadar and Tennekes 1968; Tennekes 1973). However, it was only in the 1990s and subsequent years that theory, supported by PBL flow measurements and the emergence of computational fluid dynamics (CFD) as a reliable PBL research tool, established the important role played by the free flow in determining the PBL characteristics. For an extensive list of references on such measurements and CFD computations, see Simiu et al. (2016), which addresses in detail the meteorological aspects of recent PBL research, and was deliberately published in a meteorological journal in order to benefit from reviews by boundary layer meteorology experts. In contrast, this article, which contains a summary of the main findings presented by Simiu et al. (2016), is primarily concerned with structural engineering implications of those findings, which, in the authors' opinion, need to be brought to the attention of and to be assessed by structural engineers, rather than by meteorologists.

As shown by Zilitinkevich and Esau (2002) and Zilitinkevich (2012), among others, neutrally stratified flows can be either of the truly neutral or the conventionally neutral type. Truly neutral flows are characterized by a Kazanski-Monin surface buoyancy flux parameter $\mu = 0$ and by a nondimensional number $\mu_N = N/|f| = 0$, where N is the Brunt-Väisäla frequency and f is the Coriolis parameter. Zilitinkevich and Esau (2002) and Zilitinkevich et al. (2007) note that "truly neutral flows are observed during comparatively short transition periods after sunset on a background of residual layers of convective origin," "are often treated as irrelevant because of their transitional nature, and are usually excluded from data analysis," and "neutrally stratified PBLs are almost always

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'conventionally neutral,' that is, neutral *and* developing against a background stable stratification." They are characterized by parameters $\mu = 0$, $\mu_N \neq 0$; typically, $50 < \mu_N < 300$ (Zilitinkevich and Esau 2002; Zilitinkevich et al. 2007). Additional explanations and details are included in the Appendix.

Simiu et al. (2016) showed that, at midlatitudes, for heights of up to the order of a few kilometers, (1) the mean velocities $U(z)$ (parallel to the friction velocity) are monotonically increasing with height, and (2) the velocities $V(z)$ (normal to the friction velocity), as well as the veering angles, are negligibly small for buildings with height h less than about 1 km. In this article it is shown that, because PBL heights are considerably greater than the nominal gradient heights z_g specified in ASCE 7-10, for $h > z_g$ the PBL model inherent in the standard is not appropriate. Therefore, to eliminate the possibility of unconservative designs, the standard needs to explicitly provide for an exception to its definition of gradient heights by specifying that the monotonic increase of mean wind speeds with height for elevations z such that $z_g < z < h$ must be taken into account in the design of buildings with height $h > z_g$. Also, it is noted in the next section that the mean wind profile can be described by the logarithmic law up to elevations that, at midlatitudes and for the strong wind speeds of interest in structural design, far exceed those indicated by Davenport (1965) and in ASCE 49-12 (ASCE 2012).

Features of the Conventionally Neutral PBL

Geostrophic Drag Coefficient C_g and Cross-Isobaric Angle α_0

Let u_*, G, and z_0 denote the friction velocity, the geostrophic speed, and the roughness length, respectively. For numbers μ_N typical of conventionally neutral flows (i.e., $0.5 \times 10^2 < \mu_N < 3 \times 10^2$), the dependence upon the Rossby number $Ro = G/(|f|z_0)$ of the geostrophic drag coefficient $C_g = u_*/G$ and the cross-isobaric angle α_0 (i.e., the veering angle at the gradient height) can be represented by the following expressions (Lettau 1962; Blackadar 1962; Kung 1966; Hess and Garratt 2002, p. 338; Hess 2004):

$$C_g = 0.205/(\log_{10} Ro - 0.556) \tag{1}$$

$$\alpha_0 = (173.58/\log_{10} Ro) - 3.03 \tag{2}$$

The quantities G and α_0 are obtained for any given u_*, f, and z_0 by using Eqs. (1) and (2), respectively.

PBL Height H

Zilitinkevich and Esau (2002) and Zilitinkevich et al. (2007) proposed the following expression applicable to flows for which the Kazanski-Monin surface buoyancy flux parameter $\mu \approx 0$:

$$\frac{1}{H} = \left[\frac{f^2}{(C_R)^2} + \frac{N|f|}{(C_{CN})^2}\right]\frac{1}{u_*^2} \tag{3}$$

where $C_R \approx 0.6$ and $C_{CN} \approx 1.36$. This shows that accounting for N decreases H.

Relation between PBL Flows in Different Terrain Roughness Regimes

Given the friction velocity u_* corresponding to flow over terrain with roughness length z_0, its counterpart u_{*1} corresponding to flow over terrain with roughness z_{01} is obtained as shown in the following example, reproduced from Simiu et al. (2016).

Example

For terrain with $z_0 = 0.03$ m at a location with $f = 10^{-4}\ \mathrm{s}^{-1}$ and $N = 0.01\ \mathrm{s}^{-1}$, it follows from Eq. (1) that to a storm that produces a friction velocity $u_* = 2.5\ \mathrm{m\,s^{-1}}$ there corresponds a geostrophic wind speed (i.e., the speed at the top of the PBL, i.e., for $H = 3{,}300$ m) approximately $G = 83\ \mathrm{m\,s^{-1}}$. Because the geostrophic speed G is independent of terrain roughness, it follows from the definition of Ro that for suburban terrain exposure ($z_{01} = 0.3$ m), to $G = 83\ \mathrm{m\,s^{-1}}$ there corresponds $\log_{10} Ro = \log_{10}[83/(10^{-4} \times 0.3)] = 6.44$. From Eq. (1), $C_g = 0.035$, so to flow over terrain with roughness length $z_{01} = 0.3$ m there corresponds an approximate friction velocity $u_{*1} = 83 \times 0.035 = 2.9\ \mathrm{m\,s^{-1}}$. From Eq. (3), the PBL height corresponding to $z_{01} = 0.3$ m is $H_1 = 2.9 \times 0.13/10^{-4}$, or approximately 3,800 m. From Eq. (2), the cross-isobaric angle is $\alpha_{01} = 24°$. However, as shown in Simiu et al. (2016), the veering angles at 300 m and 800 m above ground are only 2° and 6°, respectively. (Note: In this example, to differentiate these quantities from those corresponding to terrain with open exposure, for terrain with suburban exposure the subscript 1 was used in the symbols for roughness length, friction velocity, PBL height, and cross-isobaric angle.)

The mean velocity component parallel to the direction of the shear stress at the surface has been shown, on the basis of classical similarity considerations, to be described by the logarithmic law (Simiu et al. 2016, Appendix). Therefore, up to heights corresponding to small veering angles (e.g., less than 6°), the resultant mean velocity is also described by the logarithmic law, to within an approximation of less than 1%. As is shown later in this section, this means that the logarithmic law can be assumed to be valid over terrain with suburban exposure up to less than approximately 1 km.

Calculations similar to those performed in this section could also, in principle, be performed for terrains typical of centers of large cities. In the 1988 version of ASCE 7 (ASCE 1988) such terrains were classified as having Category A exposure, as distinct from Category B (suburban), C (open), and D (coastal areas directly exposed to wind blowing over bodies of water). However, Category A was eliminated in later versions of ASCE 7, for two reasons: the aerodynamic theory applicable to terrains with some degree of homogeneous roughness conditions, such as suburban terrains, becomes inapplicable to centers of large cities with tall buildings of various heights; and—although this is a moot point—for the former Category A to apply to supertall buildings, the corresponding hypothetical terrain roughness should have a fetch of the order of 1 km (ASCE 7-10, Section 26.7.3). Dealing with former Category A exposure exceeds the scope of the present article.

ASCE 7-10 Provisions on Tall Building Design

The fact that the PBL heights listed in ASCE 7-10, Table 27.9-1, are considerably lower than the heights estimated by state-of-the art PBL models means that wind loads and their effects on the supertall structures, including stresses in members and deflections, estimated in accordance with the Standard can in some cases be underestimated.

Indeed, the provisions of Section 31.4.3 of ASCE 7-10 state that loads determined by wind tunnel testing for the main wind force resisting system shall be limited so that the overall principal loads in the x- and y-directions are not less than 80% (for buildings influenced aerodynamically by the proximity of other buildings) or 50% (for other buildings) of the loads that would be determined from Part I of Chapter 27. Examples of buildings influenced aerodynamically by neighboring buildings are the World Trade Center twin towers, destroyed in the September 11, 2001, terrorist attack, and the Petronas Twin Towers in Kuala Lumpur, Malaysia. Such buildings constitute a minority among supertall buildings; nevertheless, it is important that their particular design constraints, such as those inherent in ASCE 7-10, Section 31.4.3, be taken onto account.

The determination of the loads based on Part I of ASCE 7-10, Chapter 27, must (1) satisfy the standard's specification of the wind profile in accordance with ASCE 7-10, Table 26.9-1, and (2) be performed in accordance with the gust effect factor procedure specified in ASCE 7-10, Section 26.9.5. According to Table 26.9-1, although the wind speeds are monotonically increasing only up to the gradient height z_g, they are constant for $z \geq z_g$. Therefore, because it assumes that wind speeds increase monotonically with height, the procedure of ASCE 7-10, Section 26.9.5, is only applicable for buildings with heights $h \leq z_g$. For such buildings, Requirement 2 is indeed consistent with Requirement 1. However, for buildings for which $h \geq z_g$ requirement (1) implies that the gust effect factor procedure must account for the fact that, nominally, for $z \geq z_g$, the wind velocity is constant, rather than continuing to increase, and the wind speed fluctuations vanish. The procedure of Section 26.9.5 does not cover this case.

An example is now presented to illustrate, for supertall buildings, the difference between the estimated along-wind response under the following two sets of assumptions for $z > z_g$: (1) the wind velocity is constant and the turbulence fluctuations vanish; (2) the velocity continues to increase monotonically with height and turbulence fluctuations continue to exist. (Note that under both sets of assumptions the wind flow is the same for $z \leq z_g$.) Software is available that allows the calculation of this difference (NIST 2015). Consider a building with height $h = 610$ m (2,000 ft) [i.e., a building with the same height as the 7 South Dearborn Building (Baker et al. 2000)]. It is assumed that the horizontal cross section is square with 71.6 m (235 ft) sides; the terrain exposure is suburban, with roughness length $z_0 = 0.3$ m; the building's aerodynamics are influenced by nearby buildings of comparable height; the natural frequency of vibration and the damping ratio in the fundamental mode are 0.1 Hz and 0.02, respectively; and the mean hourly wind at 10 m above ground in terrain with open exposure is 35 $\mathrm{m\,s^{-1}}$ (78.3 mph). The mean hourly wind speed at 10 m above ground over suburban terrain is estimated to be $U(10\ \mathrm{m}) \approx 29\ \mathrm{m\,s^{-1}}$. According to ASCE 7-10, the PBL height is $z_g = 366$ m, meaning that for elevations $z > z_g = 366\ \mathrm{m} = 0.6h$, $U(z) \equiv U(0.6h)$ and the turbulence intensity vanishes. Calculations that use the software mentioned earlier yield a deflection at the top of the building $\delta(h) = 1.05$ m. On the other hand, if it is assumed that the contemporary PBL model is valid (i.e., that the PBL height exceeds the height of the building h), the calculated peak deflection is $\delta(h) = 1.61$ m. The difference between the two results is because of the fact that contemporary PBL modeling entails mean wind speeds that increase, and turbulent flow fluctuations that are present, up to elevations that exceed the height $h = 610\ \mathrm{m} > z_g = 366$ m.

Section 31.4.3 of ASCE 7-10 applied to buildings with $h > z_g$ requires that the design overturning moment be no less than 80% of the calculated value compatible with the deflection $\delta(h) = 1.05$ m, that is, with the design overturning moment based on Table 26.9-1. However, this deflection would be an artifact of the unrealistic ASCE 7-10 specifications, according to which the PBL height is 366 m. In fact, because in this example the PBL height exceeds the height of the building $h = 610$ m, the intent of ASCE 7-10, Section 31.4.3, would be satisfied if the overturning moment used in design was not less than 80% of the value consistent with a peak deflection $\delta(h) = 1.61$ m, rather than $\delta(h) = 1.05$ m. The design overturning moment should therefore be, nominally, on the order of $1.61/1.05 \approx 1.5$ times greater than allowed by ASCE 7-10, Section 31.4.3. This result means that, for the restricted class of supertall buildings affected aerodynamically by neighboring buildings, ASCE 7-10, Section 31.4.3, could in some cases result in unconservative supertall building designs. This is very unlikely to be the case for buildings for which the 50% limit stipulated in ASCE 7-10, Section 31.4.3, applies.

Conclusions

A brief summary was presented of recent advances in the modeling of the PBL, which show that up to elevations of the order of a few kilometers, mean wind speeds increase monotonically with height, and the veering angle is typically negligible in practice. Those advances improve upon earlier results of PBL research that were based on asymptotic methods and did not distinguish between neutral and conventionally neutral PBL flows. The work presented in this article is applicable to large-scale synoptic storms. It is suggested that related research on thunderstorm and tropical cyclone winds is in order.

Because PBL heights are considerably greater than the nominal gradient heights z_g specified in ASCE 7-10, Table 26.9-1, for buildings with height $h > z_g$ the PBL model inherent in that table is not appropriate. Therefore, to eliminate the possibility of unconservative designs, the standard needs to explicitly provide for an exception to that table by specifying that the monotonic increase of mean wind speeds with height for elevations z such that $z_g < z < h$ must be taken into account in the design of buildings with height $h > z_g$. Doing so would eliminate the possibility that supertall buildings significantly affected aerodynamically by neighboring buildings would not satisfy the provisions of ASCE 7-10, Section 31.4.3.

Appendix. Brunt-Väisäla Frequency and Conventionally Neutral PBL Flow

Much of the theoretical work on PBL flow performed before the last few decades did not take into account the stratification of the free flow (i.e., the flow above the PBL). However, according to research results cited by, among others, Zilitinkevich and Esau (2002) and Zilitinkevich et al. (2007), the stratification, characterized by the free-flow Brunt-Väisäla frequency N, has a significant effect on the PBL. Based on the dependence of the PBL flow upon both the buoyancy flux μ at the Earth's surface (Simiu and Scanlan 1986, pp. 9, 49, for related material on buoyancy in the atmospheric boundary layer) and the free-flow Brunt-Väisäla frequency N (which pertains to the strength of stratification in the free flow), Zilitinkevich and Esau (2002) and Zilitinkevich et al. (2007) classify neutral and stable PBL flows into four categories: (1) truly neutral ($\mu = 0$, $N = 0$); (2) conventionally neutral ($\mu = 0$, $N > 0$), (3) short-lived stable ($\mu < 0$, $N = 0$), and (4) long-lived stable ($\mu < 0$, $N > 0$). Of these four categories, it is the conventionally neutral flow that is, in practice, of interest in structural engineering applications.

In stably stratified flow, when a small parcel of air with volume dV is raised a small distance z' above its initial position z, its density will be greater than the density of the surrounding air by an amount

$$\Delta\rho = -\frac{\partial\rho(z)}{\partial z} z' \tag{4}$$

The minus sign is required because in stably stratified flow $\partial\rho(z)/\partial z$ is negative. The parcel will therefore be subjected to a

J. Struct. Eng., 2017, 143(8): 06017002

downward force $g\Delta\rho dV$. After some algebra, there follows from Newton's second law

$$\frac{\partial^2 z'}{\partial t^2} = \frac{g}{\rho(z)} \frac{\partial \rho(z)}{\partial z} z' \tag{5}$$

in which viscosity effects are neglected and t denotes time. Let

$$-\frac{g}{\rho(z)} \frac{\partial \rho(z)}{\partial z} = N^2 \tag{6}$$

Eq. (5) then becomes

$$\frac{\partial^2 z'}{\partial t^2} + N^2 z' = 0 \tag{7}$$

Because for stable stratification the air density decreases as the height increases, N is real, and the solution of Eq. (7) is a harmonic function with frequency N, meaning that the parcel of air will experience oscillatory motion. Note that N^2 is proportional to the density gradient, and therefore to the strength of the stable stratification.

In the presence of horizontal flow velocities, the oscillations result in a transport of momentum between the free flow and the PBL flow. Free-flow particles that penetrate into the PBL help to increase the PBL flow speeds in the region in which that transport occurs. The net result of the transport turns out to be a reduction in the height of the PBL with respect to the height of the truly neutral PBL. The decrease of the height H as N (i.e., the strength of the stratification) increases is reflected by Eq. (3).

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