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Wind structure and codification

J. D. Holmes†

JDH Consulting, Mentone, Victoria, Australia

C. J. Baker‡

Department of Civil Engineering, University of Birmingham, Birmingham, England, U.K.

E. C. English‡†

LSU Hurricane Center, Louisiana State University, Baton Rouge, Louisiana, U.S.A.

E. C. C. Choi‡‡

School of Civil and Environmental Engineering, Nanyang Technological University, Singapore
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Abstract. The paper describes the work of the Working Group on Wind Structure, one of the International Codification Working Groups set up by the International Association of Wind Engineering in 1999. The topics of terrain and exposure, shielding and shelter, topographic effects, tropical cyclone and hurricane wind structure, and thunderstorm wind structure, are described with emphasis on their codification in wind loading codes and standards. Recommendations from the working group are given.

Keywords: codes; hurricane; shielding; terrain; thunderstorm; topography; turbulence; wind speeds.

1. Introduction

This paper discusses the general area of wind structure for use in wind loading codes and standards, on behalf of Working Group WGC, one of the working groups set up by the International Association of Wind Engineering to review and make recommendations for harmonization in international codification for wind loads.

The following sections cover the topics of terrain and exposure, shielding and shelter, topographic effects, tropical cyclone and hurricane wind structure, and thunderstorm wind structure. The recommendations from the working group on wind structure are given at the end of the paper.

† Director, jdholmes@bigpond.net.au
‡ Professor, c.j.baker@bham.ac.uk
‡† Research Associate Professor, english@hurricane,lsu.edu
‡‡ Professor, cechoi@edu.sg

2. Terrain and exposure

2.1. Velocity-height profiles

In the early years of wind engineering, the main way in which the velocity variation above ground level was specified was through the use of a power law of the form:

$$\frac{u}{u_{ref}} = \left(\frac{z}{z_{ref}}\right)^{\alpha} \tag{1}$$

where u is the mean velocity at a height z above ground level, and the subscript *ref* indicates conditions at the reference height (often taken as 10 metres). α is the power law exponent, which was found to take different values for different terrain types. α varies from values of around 0.15 in smooth coastal terrain to 0.4 in very rough urban terrain. The advantage of such an approach is its extreme simplicity and useability. However, it does have disadvantages - namely the facts that it is empirical with no theoretical base, and that, as the gradient of the curve is infinite as z approaches zero, it is generally a poor fit close to ground level. Nonetheless its use continues in a significant number of national codes, where the reference height is taken to be the gradient height (the edge of the atmospheric boundary layer) and the reference wind speed is converted to the wind speed at gradient height through a simple multiplier. Both this multiplier and the gradient height itself are taken to be functions of terrain type.

In the light of these difficulties, a number of codes have adopted the logarithmic velocity profile, which is of the form

$$u = \frac{u^*}{\kappa}\ln\left(\frac{z}{z_0}\right) = 2.5u^*\ln\left(\frac{z}{z_0}\right) \tag{2}$$

where u^* is the friction velocity, κ is von Karman's Constant approximately equal to 0.4, and z_0 is the surface roughness length of the site under consideration, which again varies with terrain type. When expressed in terms of a reference velocity and reference height, this becomes

$$\frac{u}{u_{ref}} = \frac{\ln(z/z_0)}{\ln(z_{ref}/z_0)} \tag{3}$$

This approach has the advantage of having some theoretical background - indeed the logarithmic form comes directly from classical boundary layer theory - and is a better approximation close to ground level. However, this approach tends to provide a poor fit to experimental data for heights greater than 30 to 50 m. To remedy this, a number of codes have adopted the logarithmic format, but with additional linear and non-linear terms. Perhaps the most sophisticated model of this type is that of Deaves and Harris (1981), which is based on a rigorous similarity analysis of the atmospheric boundary layer. The velocity profile is given by

$$u = 2.5u^*\ln\left(\frac{z}{z_g}\right) + 5.75\left(\frac{z}{z_g}\right) - 1.88\left(\frac{z}{z_g}\right)^2 - 1.33\left(\frac{z}{z_g}\right)^3 + 0.25\left(\frac{z}{z_g}\right)^4 \tag{4}$$

where z_g is the gradient height, the height of the atmospheric boundary layer. The theory of Deaves and Harris gives values for the gradient height explicitly. Near the ground $z = 0$, and this equation reduces to the unmodified logarithmic format. Whilst more complex than the power law and unmodified logarithmic law approaches, this method does have a rigorous analytical background, and gives a good fit to the velocity variation over a large height range. However, it is debatable whether the additional terms in Eq. (4) are justified for application to a wind loading code or standard in the height range of most buildings (say less than 50 m), and the general accuracy expected in a code or standard.

The logarithmic law, (or the related Deaves/Harris expression), is recommended by the Working Group, for use in codes and standards for terrain/height profiles in synoptic winds, due to its more rigorous analytical basis.

Now the above discussion has assumed that the predicted velocity profile extends down to ground level. Clearly, in a built up urban environment, this will not be the case. There are two basic methods for dealing with this. The first is to assume a constant velocity below a certain level, that is again usually defined to be a function of terrain type. The second method is to assume that the "effective" ground level will be above the actual ground level. This is allowed for in several codes by replacing z in the above expressions by $z-d$, where d is the displacement height. Typical values of this parameter will be given in the next section. It is sufficient to mention here that it is usually around 0.8 times the average building / local roughness height.

2.2. Terrain and exposure categories

It can be seen from Section 2.1 that to specify the velocity profile, the roughness of the local terrain needs to be specified, either through a power law exponent, or through a surface roughness length. The practice has therefore developed of defining a number of different types of terrain and allocating values of these parameters to them. The number of terrain types varies between 3 and 5 depending on the code. The roughest terrain type (with a roughness length of around 1.0 m) is usually specified as that of an inner city, whilst the smoothest is either defined as flat open country or as a coastal environment (roughness length of around 0.001 m).

2.3. Turbulence profiles

As with the velocity profiles there are two fundamentally different ways of specifying values of turbulence intensity that are required in the calculation of the dynamic structural response. The first approach is consistent with the power law approach for velocity profiles. The turbulence intensity is taken to be of the form

$$\frac{\sigma_u}{u} = k \cdot \left(\frac{z}{z_g}\right)^{\beta} \tag{5}$$

where k and β are simple functions of the chosen reference height and the power law exponent α. This approach has the same advantages and drawbacks as the power law form itself.

Now for a classic rough wall turbulent boundary layer the stream-wise turbulence component is given by

$$\frac{\sigma_u}{u^*} = 2.5\left(1 - 0.8\frac{z}{\delta}\right) \tag{6}$$

δ is the boundary layer thickness. If this equation and the logarithmic law are used together they result in the following expression for the longitudinal turbulence intensity, in the lower part of the boundary layer where (z/δ) tends to zero.

$$\frac{\sigma_u}{u} = \frac{1}{\ln(z/z_0)} \tag{7}$$

A number of codes use expressions similar to this. However, as the logarithmic law itself ceases to be valid at heights greater than about 100 m, so this formulation can also be expected to break down at such heights. The theory of Deaves and Harris however also results in an expression for turbulence intensity that is theoretically valid throughout the boundary layer. This is given by :

$$\frac{\sigma_u}{u^*} = \frac{7.5\left(1-\frac{z}{z_g}\right)\left(0.538+0.09\ln\left(\frac{z}{z_0}\right)\right)^{\left(1-\frac{z}{z_g}\right)^{1/6}}}{1+0.156\ln\left(\frac{6z_g}{z_0}\right)} \tag{8}$$

Again the use of this equation with the logarithmic law velocity profile enables an expression for turbulence intensity to be derived. It is a matter of opinion as to whether the theoretical rigour of Eq. (8) is justified by the additional complexity, for application to a code or standard.

2.4. Change of terrain

Clearly the type of terrain in which a structure is built will have a major effect upon the calculated velocity and thus upon the wind load itself. However as the upstream terrain changes, so does the atmospheric boundary layer, and at any particular site, it will usually be the case that the actual boundary layer profile will consist of a number of different profiles, the ones nearest the ground reflecting local roughness conditions, and the ones further away from the ground representing roughness conditions someway upstream. To accurately calculate the wind load some method of calculating the boundary layer development over different types of fetch is required.

The simplest approach to this problem is to essentially ignore it, but to specify that the upstream fetch must extend for a specific distance upwind of the site to enable the local site roughness to be used. The reason for this is because it is in the designer's interest to specify as rough a surface as possible, as this will result in lower design wind speeds. Thus, it is far from unknown for sites on the edge of town to be classified by designers as sites within towns for this purpose. The second more refined approach is to actually allow for such roughness changes. In the codes where this approach has been adopted, this has usually been through the use of the methods of Wood (1982), or Deaves and Harris (1981).

2.5. Comparison of code provisions on terrain-height profiles

Table 1 shows how some of the above methods are adopted by a number of major codes and standards. The number of terrain types ('categories' or 'exposures') designated by each document varies between three and five. Only two standards have attempted to include adjustments for change of terrain - i.e., for situations of non equilibrium boundary layers.

Although the number of terrain types and descriptions vary between the various documents, they can be roughly classified into three basic terrain types: 'open', 'suburban' and 'city centre'. For these three types, the designations and power law exponents and/or roughness lengths are defined in

Table 1 Summary of terrain-height formats in the major codes and standards

Code/Standard	Velocity and turbulence intensity profiles	Lower bound velocity	Number of terrain types	Change of terrain
AS/NZS1170.2:2002	Deaves and Harris (non tropical cyclone)	Constant velocity below minimum height	4	yes
ASCE-7-02	Power law	Constant velocity below minimum height	3	no
prEN 1991-1-4.6-2004	Log law	Displacement height plus constant velocity below minimum height	5	no
BS 6399:Part 2:1997	Deaves and Harris	Displacement height	3	yes
NBCC (1995)	Power law	Constant velocity below minimum height	3	no
AIJ (1993, Commentary)	Power law	Constant velocity below minimum height	5	no
ISO 4354:1997	Log law/power law		4	no

Table 2. The ‘city centre’ (‘Exposure A’) classification was discontinued in the most recent edition of ASCE-7, and is also not included in the British Standard. The AIJ Recommendations has two categories for ‘tall buildings’ (Type IV) and for ‘heavy concentration of tall buildings’ (Type V).

Tables 2(a) and 2(b) show that a numerical or alphabetical classification is used in all except the British and ISO Standards. However in ASCE-7, the classification is in the reverse order to the other documents - i.e., category B (formerly A) is the most rough exposure and category D is the least rough. This probably causes unnecessary confusion for users from other countries not used to

Table 2(a) Terrain types in the major codes and standards

Code/Standard	‘Open’			‘Urban/suburban’		
	Designations	Exponent, α	Roughness Length, z_0 (m)	Designations	Exponent, α	Roughness Length, z_0 (m)
AS/NZS 1170.2:2002	1, 2	–	0.002, 0.02 (see Note 1)	3	–	0.2 (see Note 1)
ASCE 7-02	D,C	(1/9), (1/6.5) (see Note 2)	–	B	(1/4) (see Note 2)	–
prEN 1991-1-4.6-2004	0, I, II	–	0.003, 0.01, 0.05	III	–	0.3
BS 6399:Part 2:1997	–	–	0.003, 0.03	–	–	0.3
NBCC (1995)	A	0.14	–	B	0.25	–
AIJ (1993, Commentary)	I, II	0.10, 0.15	–	III	0.20	–
ISO 4354:1997	–	0.11, 0.14	0.003, 0.03	–	0.22	0.3

Table 2(b) Terrain types in the major codes and standards

Code/Standard	'City Centre'		
	Designations	Exponent, α	Roughness Length, z_0 (m)
AS/NZS1170.2:2002	4	–	2.0 (see Note 1)
ASCE-7-02	–	–	–
prEN 1991-1-4.6-2004	IV	–	1.0
BS 6399:Part 2:1997	–	–	–
NBCC (1995)	C	0.36	–
AIJ (1993, Commentary)	IV, V	0.27, 0.35	–
ISO 4354:1997	–	0.31	3.0

Notes:
1. In AS/NZS1170.2:2002, roughness lengths are used in the Deaves and Harris model to derive gust speed multipliers for non tropical-cyclone conditions.
2. Values given in the table for ASCE-7 are for mean wind speeds. This standard also gives effective power law exponents for gust speeds.

The Working Group recommends that common definitions of terrain/exposure types should be established for codes and standards, with agreed terrain roughness lengths. Numerical designations of terrain types are preferable, and these should increase with increasing roughness.

that system. Some standardization of the power law exponents and roughness lengths would also be desirable.

The Australia/New Zealand Standard specifies different gust velocity profiles for regions where the extreme winds are dominated by tropical cyclones. These are discussed in Section 5 of this paper.

3. Shielding and shelter

Most buildings are in an urban situation, and are often surrounded by buildings of similar size. Shelter and aerodynamic interference due to upstream buildings can have a very significant effect on wind velocities, and hence on the resulting wind pressures and loads.

Lee and Soliman (1977) and Hussain and Lee (1980) carried out comprehensive studies on grouped low-rise buildings. Three flow regimes were identified depended upon the building spacing. A similar study on tropical houses, described by Holmes and Best (1979) (summarized by Holmes 1994), included a large number of grouped building situations for buildings with roofs of 10 degree pitch. This study showed that upstream buildings of the same height significantly reduced the wall pressures and the pressures at the leading edge of the roof, but had less effect on pressures on other parts of the roof. Again, the building height/spacing ratio was the major parameter, with the number of shielding rows being of lesser importance.

A more likely situation is a random distribution of shielding buildings of varying heights and widths. A series of wind-tunnel pressure measurements, for both structural loads and local cladding loads, on a flat-roofed building, situated in a variety of 'random city' environments, was carried out by Ho, *et al*. (1990, 1991). It was found that the mean component of the wind loads decreased, and the fluctuating component increased, resulting in a less-distinct variation in peak wind load with direction. The expected peak loads in the urban environment were much lower than those on the isolated building. It was also found that a high coefficient of variation (60 to 80%) of wind loads occurred on the building in the urban environment, due to the variation in location of the building.

A number of wind-tunnel studies have investigated the effects of shielding and interference on mid-rise and tall buildings, as discussed by English (1990) and Khanduri, *et al.* (1998). In some situations the presence of a nearby building can cause increased loads, particularly for torsion or cross-wind response. Interaction between a pair of buildings is usually reported in the form of a non-dimensionalized shielding, buffeting or interference factor. In most cases these factors are defined identically, as the ratio of the response of (or load on) a downstream building with an obstructing upstream or adjacent building present, to that without it. This response is commonly called shielding (or sheltering) when the presence of the obstruction reduces the load on the downstream building, interference when wind effects on either the upstream or downstream building become more severe, and buffeting when describing a crosswind or resonant response. Interference is also sometimes used as a broader term to include all types of interaction.

Codification of shielding, interference and buffeting effects is complicated by the fact that so many variables are involved in the definition of any specific configuration. The many researchers investigating the problem have each looked at a different small subset of the large number of possible configurations, making it difficult to make quantifiable generalized predictions of the sort necessary for inclusion in building codes.

English (1993) compiled and analysed data obtained from a number of wind-tunnel studies by different researchers. Each of these studies produced quantified results in the form of shielding or interference factors or coefficients, but each tested a limited, and different, set of geometric models and configurations. The various data were compiled and analysed to identify trends and patterns, but it was difficult to obtain predictable, quantified results for the range of configurations encountered using traditional methods of analysis. Fricke and English (1996) investigated the use of neural network technology to analyse the interference data. With some manipulation, this method produced very good results, allowing the prediction of the level of interference between two buildings for a broad range of separation distances, aspect ratios and levels of turbulence and a limited set of other parameters (English and Fricke 1999). These studies indicate that within these limitations, the primary factor determining the degree of shielding is the non-dimensional normalized separation distance (NSD):

$$\mathrm{NSD} = d(h+w)/2hw \tag{9}$$

where d is the distance separating the two buildings (distance between buildings, not leading edge-to-leading edge or center-to center distance), and w and h are the width and height of the front face of the obstructing building. Non-dimensionalizing the separation distance by both w and h in this manner essentially eliminates the influence of aspect ratio, except for low- or mid-rise buildings in highly turbulent flow. Except for these cases of low aspect ratio and high turbulence, where considerably more shielding occurs, terrain roughness is also shown to have a minimal influence on the results. When the separation distance is normalized just using w, as is the standard practice, aspect ratio and terrain roughness remain significant.

The only standard that explicitly attempts to codify shielding effects is the Australian/New Zealand Standard AS/NZS1170.2. This document specifies a 'Shielding Multiplier', M_s applicable to design gust velocities, that can take values less than 1.0 but no less than 0.7. The value obtained depends on a 'shielding parameter', s. Upwind buildings within a sector angle of 45 degrees, and radius $20h$, where h is the height of the building are considered. Only buildings greater than the height of the shielded building are considered (or the height of the level on the building at which pressures are being considered, in the case of the windward wall).

The shielding parameter depends on the average height, width and spacing of the shielding buildings. The values have been derived from wind-tunnel measurements on groups of low-rise buildings by Holmes and Best (1979), and Hussain and Lee (1980). In the application of the Australian Standard, a value of the Shielding Multiplier, M_s, of 0.85 for 'typical' housing configurations is generally accepted.

There is some mention of interference interaction in the draft Eurocode, but it is limited to pairs and arrays of cylinders and a discussion of wake buffeting. Increasing the wind load is recommended for a low building adjacent to a tall building surrounded by low buildings. Other codes and standards, although not specifically using reduction factors for shielding effects, often incorporate reduced velocity or pressure multipliers near the ground in urban or suburban terrain.

In general, though, the very real problem of an increase in loads on a building due to the presence of a nearby building has not been addressed by the codes. Wind tunnel tests have demonstrated significant increases in torsional loads and cross-wind response due to interference. In some cases, a decrease in the mean response may be accompanied by an increased peak response. Configurations in which the obstructing building is offset from the along-wind axis of the principal building also have been found to cause increased loading. The possibilities of the presence of an adjacent building to create dangerous increases in loads and responses is an aspect of wind effects on buildings that has been largely ignored in building codes and standards.

The Working Group finds a range of approaches to the codification of shielding and interference in the different codes and standards, and recommends that a common strategy be agreed upon and implemented. It is particularly important that building codes take steps to address the possibility of dangerous increases in loads due to interference.

4. Topographic effects

Mean and gust wind speeds are often modified considerably by natural and man-made topography in the form of escarpments, embankments, ridges, cliffs and hills. These effects have been researched since the nineteen-seventies – often inspired by the development of wind power, and the desire to site wind turbines in the most advantageous locations.

This work has improved greatly the estimation of the aerodynamic effects of shallow hills, but the speed-up effects on turbulent velocity components and gust speeds remain much less well defined, as are the effects of steep topography, which can induced separated flow.

Although topography can provide shelter as well as increased wind speed, codes and standards, with the desire to be conservative, have normally ignored the reduction effects, and provided methods only for estimating the speed-up effects of topography.

The effects of topography can conveniently be expressed in the form of a 'topographic multiplier' defined as follows (Holmes 2001) :

$$\text{Topographic Multiplier} = \frac{\text{Wind speed at height, } z\text{, above the feature}}{\text{Wind speed at height, } z\text{, above the flat ground upwind}} \tag{10}$$

This definition can be applied to the mean and peak gust wind speeds, denoted by $\overline{M}_t$ and $\hat{M}_t$ respectively.

Table 3 Terminology and symbols for topographic effects

Code/Standard	Variable	Terminology	Symbol	Relation
AS/NZS1170.2-2002	Gust wind speed	Hill-shape multiplier	M_h	$M_h = \hat{M}_t$
ASCE-7-02	Gust velocity pressures	Topographic factor	K_{zt}	$K_{zt} = \hat{M}_t^2$
prEN 1991-1-4.6-2004	Mean (10-min) wind speed	Orography factor	c_o	$c_o = \overline{M}_t$
BS 6399:Part 2:1997	Mean (1-hour) wind speed	Topographic increment	S_h	$1+S_h = \overline{M}_t$
NBCC (1995)	Mean (1-hour) wind pressure	Speed-up-factor	$\Delta S(z)$	$1+\Delta S(z) = \overline{M}_t$
AIJ (1993, Commentary)	Mean (10-min) wind speed	Topography factor	E_g	$E_g = \overline{M}_t$
ISO 4354:1997	Mean (10-min) wind pressure	Speed-up-factor	ΔS_z	$1+\Delta S_z = \overline{M}_t$

4.1. Terminology and definitions

The terminology, definitions and symbols used to represent topographic effects vary considerably between the major codes and standards. The following table summarizes various formats used in several major international and national documents.

Note that factors for which symbols are given in the Table 3 may not be interchangeable, but the relationships with the topographic multipliers for wind speed, as defined in Eq. (10), are given in the right-hand column. The 'topographic increment', S_h, as defined in the British Standard, BS6399, and the 'speed up factor', $\Delta S(z)$ or ΔS_z, used in the National Building Code of Canada and the ISO standard, when one is added to them become 'topographic multipliers' acting on mean wind speeds, as defined earlier. The topographic factor, K_{zt}, in ASCE-7 acts on gust velocity pressure, and is equivalent to the square of the topographic multiplier for gust wind speeds.

The lack of interchangiblity between the terminologies, symbols and the definitions of the factors used to specify topographic effects in the various major codes and standards, is both confusing to users, and unnecessary. *The Working Goup recommends that the topographic effects be defined in terms of a topographic multiplier acting directly on wind speed, not on velocity pressure, and not in the form of increment to which one must be added. The recommended symbols are:* $\overline{M}_t$ *and* $\hat{M}_t$*, as defined earlier.*

There are also significant differences in the formatting of topographic effects in the major codes and standards. The Australian/New Zealand Standard uses a mathematical equation format with a rectangular hyperbolic variation of gust multiplier with height, and a linear horizontal variation. ASCE-7 has a tabular form with three factors tabulated as functions of hill slope.

The Eurocode and the British Standard have the same graphical representations which allow for both horizontal and vertical variations of the speed-up factor, although the latter Standard also has a magnified form for locations near ground level.

The NBCC and ISO Standard have nearly identical formats, with mathematical representations of the vertical (exponential form) and horizontal (linear) variations of the speed-up factor. The constants in these equations are presented in tabular form as a function of hill-type.

The AIJ has a mathematical formula for the topography factor for escarpments, with a tabular form for the constants; linear interpolation is permitted for intermediate values in the Table.

4.2. Data sources

The theoretical basis for the calculation of topographic effects in many codes and standards can be traced to the work of Jackson and Hunt (1975). They showed that, for shallow hills, a linear relationship applies between the speed-up factor ($\overline{M}_t - 1$) for mean wind speeds, at the crest of a hill or escarpment, and the average upwind slope. The latter is usually taken as the average slope, ϕ, over the top half of the hill or escarpment. This can be expressed as:

$$(\overline{M}_t)_{\max} = 1 + k\phi \tag{11}$$

However, the constants of proportionality in this relationship, k, vary considerably. For example in the British Standard (BS6399:Part 2), a value of 1.2 is used for topographic features of all types, whereas in the Eurocode (prEN1991-1-4.6), a value of 2.0 is assumed.

Taylor and Lee (1984) proposed the following values of the constant, k, for various types of topography:

- 4.0 for two-dimensional ridges
- 1.6 for two-dimensional escarpments
- 3.2 for three-dimensional (axisymmetric) hills

The values of k proposed by Taylor and Lee for ridges and hills were adopted in both the National Building Code of Canada, and in ISO 4354, but higher values were used in both codes for escarpments (2.6 in the N.B.C.C. and 3.6 in ISO 4354).

Once the upwind slope of a hill or escarpment reaches a value of about 0.3 (about 17 degrees), separations occur on the upwind face and the simple formula given above cannot be applied directly. However, for slopes between about 0.3 and 1 (17 to 45 degrees), the separation bubble on the upwind slope presents an effective slope to the wind that is relatively constant. The topographic multipliers, at or near the crest, are therefore also fairly constant with upwind slope in this range. Thus for this range of slopes the actual slope, ϕ, can replaced by an effective slope ϕ', equal to about 0.3. This assumption is made in many of the major codes and standards.

The method used in the current Australia / New Zealand Standard (AS/NZS1170.2:2002) was based on numerical studies (Paterson and Holmes 1992) calibrated against wind tunnel and full-scale measurements. The method for escarpments given in the Commentary to the AIJ Recommendations is based on experimental work in Japan (Fujimoto, *et al.* 1980).

4.3. Comparison of magnitudes of topographic multipliers

To make comparisons of the magnitudes of the topographic effects predicted by the various major codes and standards, calculations were made of the effective topographic multipliers (either $\overline{M}_t$ or $\hat{M}_t$) for two locations:

a) 10 metres vertically above the crest of a shallow three-dimensional hill of height 100 metres, with an average upwind slope of 0.2,
b) 100 metres vertically above the crest of a steep two-dimensional escarpment of height 200 metres, with an average upwind slope of 0.4.

The results of these calculations are tabulated in Table 4.

Table 4 Comparison of calculated topographic multipliers

Code/Standard	Effective topographic multiplier	100 m hill $\phi = 0.2$, $z = 10$ m	200 m escarpment $\phi = 0.4$, $z = 100$ m
AS/NZS1170.2-2002	$\hat{M}_t$	1.29	1.15
ASCE-7-02	$\hat{M}_t$	1.41	1.23
prEN 1991-1-4.6-2004	$\overline{M}_t$	1.39	1.46
BS 6399:Part 2:1997	$\overline{M}_t$	1.23	1.28
NBCC (1995)	$\overline{M}_t$	1.55	1.38
AIJ (1993)	$\overline{M}_t$	(not given)	1.17
ISO 4354:1997	$\overline{M}_t$	1.55	1.53

There are significant differences between the numerical values obtained from the various codes and standards. These differences are amplified considerably when it is considered that the factors in Table 4 are squared when applied to wind pressure. There is an argument that the gust multipliers, $\hat{M}_t$, should be lower than the mean wind speed multiplier, $\overline{M}_t$, for the same topography and location, since experimental data indicates that the fluctuating (turbulent) component of a gust wind speed is affected less by the topography than is the mean wind speed. However, this is not generally reflected by the values in Table 4 – for example the gust multiplier in the ASCE-7 Standard is higher than the mean multipliers, for the hill site, in both the draft Eurocode and in the British Standard, and for the escarpment in the AIJ Recommendations.

Since sites vertically above the crest of the topography were chosen as examples, the values obtained do not show any differences in the horizontal variation of topographic multiplier upwind and downwind from the crest.

Other points worth noting with respect to Table 4 are as follows:

- Although the methods in the draft Eurocode and the British Standard are nearly identical, the 'speed-up factors' ($\overline{M}_t - 1$), in prEN1991-1-4.6 are 67% higher than those in BS6399 for both cases. This is because of the larger value of *k* assumed in the Eurocode as discussed in Section 4.2.
- The methods in the National Building Code of Canada and ISO 4354 are identical for the hill, but the 'speed-up factor' ($\overline{M}_t - 1$), for the escarpment is 38% higher in ISO4354. This is because of the larger value of *k* assumed in ISO 4354 for escarpments, as discussed in Section 4.2

The differences indicated by Table 4 can cause large differences in calculated wind loads – between the largest and smallest values in Table 4, there is a 59% change in the topographic factor on wind pressure for the hill, and 77% for the escarpment! Such large differences do not exist in the source experimental data on topographic effects.

The Working Group recommends that large differences between numerical values for topographic effects given in current codes and standards should be resolved.

5. Tropical cyclone wind structure

Measurements from a tall tower on the North-west coast of Australia, and SODAR measurements from Okinawa (Amano, *et al.* 1999) indicated that the mean velocity profiles, in the region of high winds just outside the eye wall of tropical cyclones and typhoons, often reached a maximum value at low heights with relatively constant velocities in the mixed layer at greater heights. These characteristics are also consistent with numerical models of tropical cyclones.

The Australian Standard appears to be the only major international document to recognize the differences between wind structure in the maximum wind region of tropical cyclones, and in higher latitude synoptic gales. AS1170.2-1989 incorporated a constant terrain-height multiplier, above 100 metres height, into profiles of both mean and gust wind speeds in the 1989 edition. This has continued with the Australia/New Zealand Standard of 2002.

There is also strong evidence that turbulence intensities are higher in tropical cyclones in comparisons to boundary layer winds from synoptic storms at higher latitudes. This has significance for calculation of dynamic effects, and for the development of gust envelope profiles in codes and standards. Again the Australian Standard has specified higher turbulence intensities for tropical cyclones.

Recent measurements by dropsondes in Atlantic and Caribbean hurricanes (e.g. Powell, *et al.* 2003) are providing useful information on the profiles of these storms, but the data obtained, apparently representing a 5-second non-simultaneous gust speed through a storm, will require additional processing to be interpreted as 10-minute mean wind speeds and 3-second gust envelopes profiles, that are required for wind loading codes and standards.

In summary, the Working Group believes that the differences between velocity profiles in the regions of high winds of tropical cyclones (hurricanes and typhoons) and for higher latitude synoptic winds have largely gone unrecognised in wind codes and standards. Although there is a need for more measurements from tall towers, there are clearly significant differences in these velocity profiles that should be incorporated into future editions of codes and standards.

6. Thunderstorm wind structure

Although severe thunderstorm downdrafts are dominant windstorms in many parts of the world, no current code or standard currently addresses the particular wind structure of these storm types, including gust velocity profiles for design applications. This is partly because of the lack of appreciation of the importance of thunderstorm winds in the past, and partly because of the lack of data on the wind structure of these events. However, the latter is presently being addressed by extensive measurement programmes in both Texas and Singapore. These storms are clearly non-stationary, and the processing of measurement data requires different techniques to those based on the model of stationary random processes, usually assumed when processing data to determine wind structure in synoptic winds, such as gales and tropical cyclones.

The origin of severe thunderstorm gusts is a downdraft of cold air of finite width emerging as a horizontal gust front near ground level. This leads to significant differences in the wind structure from those for synoptic winds, as discussed in previous sections:

- Wind speeds will not increase monotonically to heights beyond the thickness of the original downdraft jet.
- The effects of terrain and topography are very different.
- The largest gust is probably well correlated over both horizontal and vertical separations.

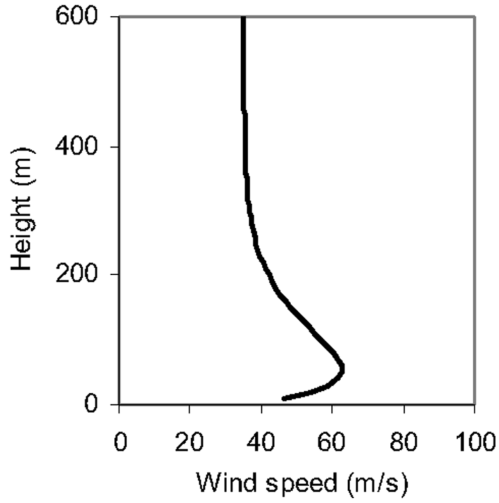

Fig. 1 Speculative thunderstorm downburst wind gust profile

The latter property was illustrated by the gust structure of a supercell rear-flank downburst measured at Lubbock, Texas, over seven anemometers at heights between 3m and 15m, spaced over a distance of 1.6 km (Gast and Schroeder 2003). A measurement of integral length scale calculated over the peak 2 minutes of the storm gave a value of 350 m, a value much higher than that found in synoptic storms at the same height. The data from this storm also showed very little variation in the recorded peak gust speeds with height up to 15 m, – a result which may be significant for low-rise buildings.

Choi and Hidayat (2003) measured wind profiles from a number of thunderstorm events on a 150-metre tower in Singapore. The profiles were classified into four groups, only one of which followed the power law profile of Eq. (1), and these were events where the thunderstorm occurred some distance away from the measuring station. However, the events that produced the measured profiles generated wind speeds considerably lower at the tower position than those representative of design speeds. Hopefully, vertical profiles in more severe thunderstorms will be recorded at both Singapore and Texas in the near future.

In the absence of definitive vertical design profiles for thunderstorm downdrafts based on measurements, a speculative profile has been developed to satisfy an immediate design requirement in a severe thunderstorm environment. This profile is shown in Fig. 1.

A mathematical form for this downburst profile is as follows:

$$U = U_{amb} + \left(\frac{\lambda R^2}{2r}\right)[1 - e^{-(r/R)^2}](e^{-z/z^*} - e^{-z/\varepsilon}) \tag{12}$$

where,

r is the radial coordinate from the centre of the downburst
R is the characteristic radius of the downburst 'shaft'
z is the height above the ground
z^* is a characteristic height out of the boundary layer
ε is a characteristic height in the boundary layer

λ is a scaling factor, with dimensions of [time]$^{-1}$
U_{amb} is the ambient (background) wind speed , also incorporating the forward speed of the storm

λ is the scaling factor that determines the magnitudes of the velocity in the downburst profile. i.e., this factor is directly proportional to the velocity magnitude.

The second part of the right-hand side of Eq. (12) is a profile suggested by Oseguera and Bowles (1988) for a stationary downburst. The parameters that were used to develop the profile in Fig. 1 are as follows:

$$R = 1000\ \text{m};\ (r/R) = 1.121;\ z^* = 60\ \text{m};\ \varepsilon = 50\ \text{m};\ \lambda = 1.3;\ U_{amb} = 35\ \text{m/s}$$

This profile is currently scaled to a value of 40 m/s at 4 m height, and gives a value of 57 m/s at 100 m height. The maximum gust speed is 63 m/s at a height of 55 metres. It can be re-scaled to match appropriate long return period design wind speeds – for example a 50-year return gust speed at 10 m.

It should be emphasized that this is a tentative profile. Measurements by Choi and Hidayat (2003) indicated that the maximum gust speeds for some storms (even for storms occurring close to the measuring station) could occur at heights above 150 m. Although it is envisaged that terrain roughness has little effect on the profile, more recent studies by Choi showed that a rougher terrain may push the height of the peak wind speed to a higher elevation than a smooth terrain. Further research is needed to clarify the true nature of a thunderstorm wind profile and the uncertainties associated with the equation.

The Working Group finds that there is an urgent need to incorporate the wind structure of severe thunderstorms into codes and standards, given the importance of these wind types in many regions of the world. A speculative design profile, for the variation of the gust wind speed with height, is given in this paper; however this needs to be refined when sufficient full-scale data is available.

7. Recommendations on codification of wind structure

The recommendations of the Working Group, as given in the main text, are summarized as follows :

(1) The logarithmic law, (or the related Deaves/Harris expression), is recommended for terrain/height profiles in synoptic winds, due to its more rigorous analytical basis.
(2) Common definitions of terrain/exposure types should be established, with agreed terrain roughness lengths.
(3) Numerical designations of terrain types are preferable, and these should increase with increasing roughness.
(4) A common strategy for the codification of shielding and interference should be agreed upon and implemented. It is particularly important that building codes take steps to address the possibility of dangerously increased loads due to interference.
(5) For the effects of topography on wind speed, common formats and terminologies for topographic factors or multipliers should be used.
(6) The large differences between numerical values for topographic effects given in current codes and standards should be resolved.
(7) The Working Group believes that the differences between velocity profiles in the regions of

high winds of tropical cyclones (hurricanes and typhoons) and for higher latitude synoptic winds have largely gone unrecognised in wind codes and standards. Although there is a need for more measurements from tall towers, there are clearly significant differences in these velocity profiles that should be incorporated into future editions of codes and standards.

(8) There is an urgent need to incorporate the wind structure of severe thunderstorms into codes and standards, given the importance of these wind types in many regions of the world. A speculative design profile, for the variation of the gust wind speed with height, is given in this paper; however this needs to be refined when sufficient full-scale data is available.

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