

# INTERNATIONAL STANDARD

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4354**

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## Wind actions on structures

*Actions du vent sur les structures*



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## Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

ISO 4354 was prepared by Technical Committee ISO/TC 98, *Bases for design of structures*, Subcommittee SC 3, *Loads, forces and other actions*.

This second edition cancels and replaces the first edition (ISO 4354:1997), which been technically revised.

## Introduction

This International Standard is intended for use by countries without an adequate wind loading standard and as a bridge between existing International Standards. The data in the annexes, with the exception of Annex A, whilst formally only informative, and limited to the most common usage, are intended for use within the definitions in this International Standard. Additional data will be provided from time to time in ISO Technical Reports for use on the same basis.



# Wind actions on structures

## 1 Scope

This International Standard describes the actions of wind on structures and specifies methods of calculating characteristic values of wind loads for use in designing buildings, towers, chimneys, bridges and other structures, as well as their components and appendages. The loads are suitable for use in conjunction with ISO 2394 and other International Standards concerned with wind loads. In particular, this International Standard facilitates the conversion between peak and mean wind speed methodologies and covers the three main storm types, synoptic winds, thunderstorms and tropical cyclones (hurricanes and typhoons).

This International Standard provides the basic methods from which to determine wind loading analytically through the determination of design pressures or orthogonal along-wind and cross-wind forces and moments for structures of simple shape and wind directionality effects, and through wind tunnel or computational determinations of pressure, forces and moments for structures with complex shapes and wind directionality effects resulting in complex combinations of forces and moments.

Structures of unusual nature, size or complexity (e.g. tall buildings, long span bridges, large span roofs, guyed masts, offshore and moving structures) typically require a special engineering study; some guidance is given on the limitations of this International Standard in these cases.

Two methods of analytical determination of design wind loads are given in this International Standard, one based on a peak velocity and the other on a mean velocity. Both methods can be used when dynamic response effects are important, and where they are not important only the peak-velocity method is used in this International Standard by taking the peak dynamic response factor to be unity. To simplify presentation, the method based on the peak velocity is given in the main body of this International Standard and the method based on the mean velocity is given in a normative Annex A.

## 2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 2394, *General principles on reliability for structures*

### 3 Symbols

| Symbol         | Term                                                                         | Unit      |
|----------------|------------------------------------------------------------------------------|-----------|
| $A$            | Tributary or local area (area of application of pressure coefficient $C_p$ ) | $m^2$     |
| $A_{ref}$      | Reference area for force on overall structure or part of structure           | $m^2$     |
| $C_{dyn}$      | Peak dynamic response factor                                                 | 1         |
| $C_{dyn, m}$   | Mean dynamic response factor                                                 | 1         |
| $C_{exp}$      | Peak exposure factor                                                         | 1         |
| $C_{exp, m}$   | Mean exposure factor                                                         | 1         |
| $C_F$          | Force coefficient                                                            | 1         |
| $C_{Fm}$       | Mean force coefficient                                                       | 1         |
| $C_p$          | Pressure coefficient (time and spatially averaged)                           | 1         |
| $C_{\sigma F}$ | Standard deviation force coefficient                                         | 1         |
| $F$            | Peak force                                                                   | N         |
| $F_{loc}$      | Peak force on a tributary or local area                                      | N         |
| $F_m$          | Mean force                                                                   | N         |
| $g$            | Peak factor                                                                  | 1         |
| $g_v$          | Wind speed peak factor                                                       | 1         |
| $h$            | Height                                                                       | m         |
| $I_v$          | Wind speed turbulence intensity                                              | 1         |
| $p$            | Pressure                                                                     | $Nm^{-2}$ |
| $q_{ref, m}$   | Regional reference mean dynamic pressure                                     | $Nm^{-2}$ |
| $q_{site}$     | Site peak dynamic pressure                                                   | $Nm^{-2}$ |
| $q_{site, m}$  | Site mean dynamic pressure                                                   | $Nm^{-2}$ |
| $V$            | Peak wind speed                                                              | $ms^{-1}$ |
| $V_{hcr}$      | Critical wind speed at the top of the structure                              | $ms^{-1}$ |
| $V_m$          | Mean wind speed                                                              | $ms^{-1}$ |
| $V_{ref}$      | Regional peak reference wind speed (with return period)                      | $ms^{-1}$ |
| $V_{ref, m}$   | Regional mean reference wind speed                                           | $ms^{-1}$ |
| $V_{site}$     | Site peak velocity                                                           | $ms^{-1}$ |
| $V_{site, m}$  | Site mean velocity                                                           | $ms^{-1}$ |
| $\sigma_F$     | Standard deviation of force                                                  | N         |

### 4 Wind actions

Wind actions that shall be considered in the design of the structure can produce the following:

- excessive forces or instability in the structure or its structural members or elements;
- excessive deflection or distortion of the structure or its elements;
- repeated dynamic forces causing fatigue of structural elements;

- d) aeroelastic instability, in which motion of the structure in wind produces aerodynamic forces augmenting the motion;
- e) excessive dynamic movements causing concern or discomfort to occupants or onlookers;
- f) effects of interference from existing and potential future buildings.

NOTE Wind pressure and force given in this International Standard are equivalent static wind loads and not pure external excitations. As the equivalent static wind loads are essentially based on linear elastic building and structure behaviour, it is necessary to give careful attention if they are applied to design in the plastic region.

## 5 Wind pressure

For the actions referred to in Clause 4 a), b), c) and e), the effective wind pressure,  $p$ , shall be determined from a relationship incorporating the site dynamic pressure,  $q_{\text{site}}$ , defined in Clause 7 and Clause 8, a pressure coefficient,  $C_p$ , and a dynamic response factor,  $C_{\text{dyn}}$ , of the general form of Equation (1):

$$p = q_{\text{site}} \times C_p \times C_{\text{dyn}} \quad (1)$$

The wind pressure is assumed to act statically in a direction normal to the surface of the structure or element, except where tangential frictional forces are specifically identified. Both internal and external pressures shall be considered. Integration of pressures shall be undertaken to obtain global forces or forces for defined tributary areas.

The effects of wind from all directions shall be considered.

## 6 Wind force

For some structures, it may be appropriate to represent the wind forces,  $F$ , by their resultants. These resultants shall include along-wind (drag), cross-wind (lift), torsional and overturning actions. Different magnitudes and distributions of the wind force can be necessary to evaluate the actions described in Clause 4 a), b), c) and e).

The derivation of effective wind forces on an element, or resultant forces and moments, shall be determined by using either the peak reference dynamic pressure given here, or the mean reference dynamic pressure given in Annex A.

The peak reference pressure method assumes that the dynamic effects can be represented by a maximum or peak loading effect based on a peak reference pressure combined with a mean pressure coefficient, (or mean pressure coefficient modified for local effects relating to area of application and statistical characteristics), and a peak dynamic response factor,  $C_{\text{dyn}}$ , from the general relationships given in Equations (2) and (3):

$$F_{\text{loc}} = q_{\text{site}} \times C_p \times C_{\text{dyn}} \times A \quad (2)$$

$$F = q_{\text{site}} \times C_F \times C_{\text{dyn}} \times A_{\text{ref}} \quad (3)$$

Equation (2) is used for the force on a tributary or local area,  $A$ . Equation (3) is used for the total force on the whole structure or part of the structure. The value of  $C_{\text{dyn}}$  can be taken as 1,0 except where the structure is dynamically wind-sensitive, as described in Annex E.

In many cases total loads on whole structures will be determined from loads determined for various components, or facades, or from along-wind and cross-wind components. These forces contribute simultaneously but are not usually well correlated. Methods for determining load combinations are given in Annex G.

It is important when using the dynamic method that the ways in which the equivalent static wind forces are distributed include not only the mean and fluctuating (background) wind forces acting on the structure's exterior, but also the inertial forces due to motions of the structure's mass.

## 7 Site peak dynamic pressure

The site peak dynamic pressure,  $q_{\text{site}}$ , shall be determined from the regionally derived reference wind speed,  $V_{\text{ref}}$ , along with appropriate exposure factors,  $C_{\text{exp}}$ , relating to wind speed for the site defined by the expression:

$$q_{\text{site}} = 0,5 \times \rho (V_{\text{site}})^2 \quad (4)$$

In Equation (4) the peak design wind speed locally at the site, adjusted for local exposure conditions, is given by Equation (5):

$$V_{\text{site}} = V_{\text{ref}} C_{\text{exp}} \quad (5)$$

where the exposure factor is determined as described in Clause 8.

The reference wind speed is normally the specified value of the wind speed for the geographical area in which the structure is located. It refers to a standard exposure (i.e. roughness, height and topography), averaging time and probability of exceedence in one year (which can be approximated by an average return period for design application as required from serviceability to ultimate limit state determinations). In some situations, the reference wind speed can be specified as varying with direction. In the annexes of this International Standard the standard exposure is at 10 m height in open country terrain and  $q_{\text{site}}$  is based on a maximum 3 s mean gust wind speed,  $V$ .

Analysis procedures and values are given in Annex B and Annex C.

In certain cases, critical loading can occur at wind speeds differing from, and perhaps lower than, that specified above (e.g. due to vortex shedding). These critical wind speeds (with reference to height  $h$ ) are denoted  $V_{\text{hcr}}$  and substituted for  $V_{\text{site}}$ . These cases are discussed in Annex E.

## 8 Exposure factor

The exposure factor,  $C_{\text{exp}}$ , relating to wind speed, accounts for the variability of the wind speed at the site of the structure for each storm type, due to

- a) the height above ground level,
- b) the roughness of the terrain (including change of roughness), and
- c) the topography.

Values of the exposure factor are given in Annex C, and can vary with wind direction. Further guidance on the application of directional design wind speeds is given in Annex C.

## 9 Pressure and force coefficients

A pressure coefficient,  $C_p$ , is an aerodynamic wind-induced pressure expressed as a fraction of the reference pressure. A force coefficient,  $C_F$ , is an aerodynamic wind-induced force expressed as a ratio of the aerodynamic force exerted on a structure or its parts to a reference pressure multiplied by a reference area.

Pressure coefficients are specified as appropriate fractile values of the respective extreme actions. The fractile value to be used is defined in Annex D.

Pressure and force coefficients are influenced by the shape of the structure, the exposure, the relative wind direction, the Reynolds number and the averaging time. Values of pressure and force coefficients are presented in Annex D in tables as non-simultaneous values for the design of cladding or parts of the structure and in figures as simultaneous distributions for the design of the load-bearing structure.

Enclosed structures are subject to internal pressures determined by the size and distribution of the openings in the building envelope and by any pressurization, mechanical or otherwise. Allowance shall be made for these by combining pressure coefficients for the external pressures with those for the internal pressures.

Pressure and force coefficients shall be determined from one of the following sources:

- a) Annex D;
- b) appropriate wind tunnel tests, as described in Annex H;
- c) appropriate computationally based data, as described in Annex I;
- d) other codes or standards, provided that appropriate adjustment is made for any discrepancies, e.g. in averaging time and exposure from those used in this International Standard, and provided that adequate provision is made for a dynamic response factor.

## 10 Dynamic response factor

The dynamic response factor,  $C_{dyn}$ , accounts for the following actions of the wind:

- a) fluctuating pressures due to random wind gusts acting over all or a part of the surface area of the structure;
- b) fluctuating pressures in the wake of the structure (vortex shedding forces), producing resultant forces acting cross-wind, as well as torsionally and along-wind;
- c) fluctuating pressures induced by the motion of the structure due to wind.

Information on these effects and appropriate values of the dynamic response factor is given in Annex E.

## 11 Criterion for aeroelastic instability

For structures affected by the wind actions specified in Clause 4 d) that cause aeroelastic instability, it is necessary to show that the performance of the structure, without further application of a load factor, is acceptable up to a wind speed somewhat higher than the design peak wind speed for the structure. Unless alternative rational procedures are available, this wind speed shall be taken as no less than the ultimate limit state site peak velocity,  $V_{site}$ , or 1,5 times the ultimate limit state 10-min mean design wind speed for the site location and height of the structure.

## 12 Methods of determination of wind loads

Two methods of determining design wind loads are given in this International Standard, one based on a peak velocity pressure and the other on a mean velocity pressure. Both methods are intended for use in a detailed way when dynamic response effects are important with an appropriate value of either a peak or mean dynamic response factor, guidance for which is given in Annex E. When dynamic response effects are not important, such as for the design of cladding for most typical structures and the design of the main structural systems of small- to medium-sized structures with little dynamic response effect, the peak velocity pressure method is intended for use in a simplified way by taking the peak dynamic response factor,  $C_{dyn}$ , to be unity.

For certain wind-sensitive structures specialist supplementary studies are recommended. Structures sensitive to wind include those which are particularly flexible, slender, tall or of light weight and those within complex surroundings. Unusual geometry is able to also give rise to an unexpectedly large response to wind. In these instances, supplementary studies by an expert in the field are recommended and these typically include wind tunnel tests. These tests can be used to establish details of the overall structural loads and the distribution of external local pressures. Details of suitable testing procedures are given in Annex H.

Both methods of analysis are intended for use with performance-based and limit state design methods, the requirements for which are introduced at the choice of an appropriate probability of exceedance for the regional reference wind speed, defined in Clause 7.

This International Standard may be used to interpret between national and regional wind loading standards by using the relationships given in Annex B and Annex C. In using this International Standard or interpreting between national standards, it is essential that account be taken of the storm type most applicable to both the ultimate limit state and the serviceability design.

Alternative methods of analysis to those recommended in this International Standard may be permitted provided it can be demonstrated that the level of safety achieved is generally equivalent to that achieved in this International Standard. Guidance on the level of safety is given in Annex J.

## Annex A (normative)

### Mean velocity method

#### A.1 General

Two methods for analytical determination of design wind loads are given in this International Standard, one based on a peak velocity that has been presented in the main body of this International Standard, and the other on a mean velocity that is to be presented in this normative Annex A. The mean velocity method has its main application in the determination of dynamic response effects because it transparently represents the response of the structure in terms of mean and fluctuating components, which is a more accurate description of the response process and more appropriate when considering complex structures requiring load distributions with height and load combinations as used in determinations based on wind tunnel model measurements.

#### A.2 Wind force analysis procedures

The mean velocity method assumes that the dynamic effects can be represented by a general expression for the peak loading effect,  $F$ , made up from the addition of a mean force component,  $F_m$ , and a fluctuating force component made up from the product of a peak factor,  $g$ , and the standard deviation of the force,  $\sigma_F$ , as given in Equation (A.1):

$$F = F_m + g \times \sigma_F \quad (\text{A.1})$$

where the mean and standard deviation forces can be obtained using mean and standard deviation force coefficients,  $C_{Fm}$  and  $C_{\sigma F}$ , as given in Equations (A.2) and (A.3):

$$F_m = q_{\text{site}, m} \times C_{Fm} \times A_{\text{ref}} \quad (\text{A.2})$$

and

$$\sigma_F = q_{\text{site}, m} \times C_{\sigma m} \times A_{\text{ref}} \quad (\text{A.3})$$

To facilitate the conversion to the peak dynamic response factor,  $C_{\text{dyn}}$ , a mean dynamic response factor,  $C_{\text{dyn}, m}$ , (often referred to as a gust effect factor for along-wind forces) can be given as Equation (A.4):

$$C_{\text{dyn}, m} = F/F_m = 1 + g \times \sigma_F/F_m \quad (\text{A.4})$$

And for local force,  $F_{\text{loc}}$ , on tributary or local area,  $A$ , as Equation (A.5):

$$F_{\text{loc}} = F_m \times C_{\text{dyn}, m} = q_{\text{site}, m} \times C_p \times C_{\text{dyn}, m} \times A \quad (\text{A.5})$$

NOTE  $C_p$  in this application is the actual mean value and not a modified mean value.

For overall force,  $F$ , on a structure with reference area,  $A_{\text{ref}}$ , Equation (A.6) is used as follows:

$$F = F_m \times C_{\text{dyn}, m} = q_{\text{site}, m} C_{Fm} \times C_{\text{dyn}, m} \times A_{\text{ref}} \quad (\text{A.6})$$

The peak and mean dynamic response factors can be linked through the relationship between the peak and mean wind speeds with the introduction of a wind speed peak factor,  $g_v$ , and turbulence intensity,  $I_v$ , as given in Equations (A.7) and (A.8):

$$V = V_m (1 + g_v I_v) \quad (\text{A.7})$$

$$C_{\text{dyn}} = C_{\text{dyn}, m} / (1 + g_v I_v)^2 \quad (\text{A.8})$$

[and as an approximation, for low turbulence intensity,  $C_{\text{dyn}} = C_{\text{dyn}, m} / (1 + 2g_v I_v)$ ]

### A.3 Site mean dynamic pressure

The site mean dynamic pressure,  $q_{\text{site}, m}$ , shall be determined from regionally derived mean reference wind speed,  $V_{\text{ref}, m}$ , along with appropriate exposure factors,  $C_{\text{exp}, m}$ , relating to wind speed, for the site defined using Equation (A.9):

$$q_{\text{site}, m} = 0,5 \times \rho (V_{\text{site}, m})^2 \quad (\text{A.9})$$

where

$$V_{\text{site}, m} = V_{\text{ref}, m} \times C_{\text{exp}, m} \quad (\text{A.10})$$

In Equation (A.10),  $V_{\text{site}, m}$  is the mean design wind speed relating to the local exposure conditions and height of the structure as described in A.4.

The reference wind speed is normally the specified value of the wind speed for the geographical area in which the structure is located. It refers to a standard exposure (i.e. roughness, height and topography), averaging time and probability of exceedence in one year (which can be approximated by an average return period for design application as required from serviceability to ultimate limit state determinations). In some situations, the reference wind speed can be specified as varying with direction. In the Annexes of this International Standard the standard exposure is at 10 m height in open country terrain and  $q_{\text{ref}, m}$  is based on a maximum 10-min mean wind speed,  $V_{\text{ref}, m}$ .

Analysis procedures and values are given in Annex B and Annex C.

In certain cases, critical loading can occur at wind speeds differing from that specified above (e.g. due to vortex shedding). These critical wind speeds (with reference to height,  $h$ ) are denoted  $V_{\text{hcr}}$  and are substituted for  $V_{\text{ref}}$ . These cases are discussed in Annex E.

### A.4 Mean exposure factor

The mean exposure factors,  $C_{\text{exp}, m}$ , relating to mean wind speed account for the variability of the mean wind speed at the site of the structure, for each storm type, due to

- a) the height above ground level,
- b) the roughness of the terrain (including change of roughness), and
- c) the topography.

Values of the mean exposure factor are given in Annex C and can vary with wind direction. Further guidance on the application of directional design wind speeds is given in Annex C.

## Annex B (informative)

### Determination of reference wind speed

#### B.1 General

Clause 7 defines site peak and mean dynamic pressures in terms of reference wind speeds and exposure factors. The reference wind speeds for any probability of exceedance in one year (average return period) shall be determined from regionally derived reference wind speeds, and for use in this International Standard the two reference wind speeds will be referenced to standard averaging times and exposure, defined as follows:

- $V_{\text{ref}}$  is the maximum wind speed averaged over 3 s referenced to a height of 10 m over flat open country terrain;
- $V_{\text{ref, m}}$  is the maximum mean wind speed averaged over 10 min referenced to a height of 10 m over flat open country terrain.

Many national standards are based on annual extremes which can be appropriate where a single storm type causes the extremes. However, generally, yearly extremes do not form an appropriate basis for the extreme value analysis of wind speeds. This is especially true if the respective storm phenomenon tends to occur in families or clusters. Then, in a specific (calendar) year more than one event corresponding to the analysed storm type might be obtained, while in another year no event of the analysed storm type has occurred. In such cases, the ensemble of yearly extremes contains irrelevant data and neglects other relevant data. The ensemble therefore should consist of independent extremes above an appropriate threshold for each storm type.

#### B.2 Analysis procedures

The defined reference wind speeds shall be obtained from regional wind speeds, which, if not referenced as given in the definitions in Clause B.1, shall be converted by the following procedures.

- a) Conversion for wind speeds referenced to different terrain roughness or height,  $V_{\text{tr, z}}$ , shall use the exposure factors,  $C_{\text{exp}}$ ,  $C_{\text{exp, m}}$ , given in Annex C for the appropriate storm type as given in Equations (B.1) and (B.2):

$$V_{\text{ref}} = \frac{V_{\text{tr, z}}}{C_{\text{exp}}} \quad (\text{B.1})$$

$$V_{\text{ref, m}} = \frac{V_{\text{tr, z, m}}}{C_{\text{exp, m}}} \quad (\text{B.2})$$

- b) Conversion to wind speeds,  $V_T$ , referenced for different averaging times,  $T$ , shall use an averaging time factor,  $k_T$ , which is based on a peak factor,  $g_v$ , and the turbulence intensity,  $I_v$ , as given in Equations (B.3) and (B.4):

$$V_T = k_T V_{T=3\,600\text{ s}} \quad (\text{B.3})$$

$$k_T = 1 + g_v I_v \quad (\text{B.4})$$

$k_T$  relates to the maximum wind speed averaged over a given period of  $T$  seconds within the hourly mean wind speed for a given hour.

$g_v$  is a peak factor that depends primarily on the time over which the maximum wind speed is averaged,  $T$ , and weakly dependent on height. A full derivation methodology is given in References [2], [3] and [4], as summarized in Reference [5]. For this International Standard, average values of  $g_v$  for heights between 3 m and 300 m are given in Table B.1 along with an evaluation of  $k_T$  for a range of values of  $T$  for the specific reference conditions of  $z = 10$  m and  $z_0 = 0,03$  m.

$I_v$  is the turbulence intensity defined as the standard deviation of wind speed divided by the hourly mean wind speed, using Equation (B.5):

$$I_v = \frac{\sigma_v}{V_{m, T=3\ 600\ s}} \quad (\text{B.5})$$

**Table B.1 — Averaging peak factors,  $g_v$ , and evaluation of reference averaging time factor,  $k_T$ ,  $z$**

| Averaging time<br>$T$<br>s | Average peak factor<br>$g_v$ | Reference averaging time factor<br>$k_T, z = 10\text{ m}, z_0 = 0,03\text{ m}$ |
|----------------------------|------------------------------|--------------------------------------------------------------------------------|
| 1                          | 3,90                         | 1,62                                                                           |
| 3                          | 3,00                         | 1,53                                                                           |
| 10                         | 2,40                         | 1,42                                                                           |
| 30                         | 1,65                         | 1,27                                                                           |
| 100                        | 0,90                         | 1,15                                                                           |
| 600                        | 0,28                         | 1,05                                                                           |
| 3 600                      | 0                            | 1,00                                                                           |

The most common conversions needed for reference conditions in relation to averaging time,  $T$ , are:

- $V_{\text{ref}, T=3\text{ s}} = 1,53 V_{\text{ref}, T=3\ 600\text{ s}}$
- $V_{\text{ref}, T=600\text{ s}} = 1,05 V_{\text{ref}, T=3\ 600\text{ s}}$
- $V_{\text{ref}, T=3\text{ s}} = 1,46 V_{\text{ref}, T=600\text{ s}}$

Anemometer measurements might not have been made in the open country reference conditions of  $z_0 = 0,03$  m and more detailed correction might be needed to obtain the appropriate peak factor as well as the conversions given by Equations (B.1) and (B.2), such as using Equation (C.3) with Figure C.1.

The hourly mean wind speed is meaningful for synoptic storms, but for tropical cyclone storms and thunderstorms there are no statistically stationary values of the hourly mean wind speed. In these latter cases an equivalent 10 min mean wind speed can be used in this International Standard to facilitate the determination of the dynamic response, although the use of the 3 s wind speed is recommended in thunderstorm climates. In addition, historical wind speed data in thunderstorm climates need to be referenced to averaging times of 3 s or less for the meaningful determination of extreme value design wind speeds.

## Annex C (informative)

### Determination of exposure factors

#### C.1 General

Clause 8 defines the exposure factors in terms of the variation of the reference wind speeds and consequently, the site peak and mean velocity pressures, with height, terrain roughness, change in terrain roughness and topography for the various storm types. The exposure factors will be made up of factors for each of these phenomena as shown in Equations (C.1) and (C.2):

$$C_{\text{exp}} = k_{\text{tr}, z} \times k_{\text{trchange}} \times k_{\text{topog}} \quad (\text{C.1})$$

$$C_{\text{exp}, m} = k_{\text{tr}, z, m} \times k_{\text{trchange}, m} \times k_{\text{topog}, m} \quad (\text{C.2})$$

where

$k_{\text{tr}, z}$  is the peak terrain roughness and height exposure factors;

$k_{\text{tr}, z, m}$  is the mean terrain roughness and height exposure factors;

$k_{\text{trchange}}$  is the peak terrain roughness change exposure factors;

$k_{\text{trchange}, m}$  is the mean terrain roughness change exposure factors;

$k_{\text{topog}}$  is the peak topography exposure factors;

$k_{\text{topog}, m}$  is the mean topography exposure factors;

$z$  is the height above ground level.

#### C.2 Wind profiles over flat terrain

Values of the terrain roughness and height exposure factors will be given for three storm types, along with values of turbulence intensity.

##### C.2.1 Synoptic storm profiles

Synoptic storm hourly mean wind speed and turbulence intensity profiles for four terrain roughness categories will be defined by the following logarithmic law relations (after Reference [2]) to fit roughness length values of  $z_0 = 0,003, 0,03, 0,3$  and  $3,0$  m, defined as terrain roughness categories 1, 2, 3 and 4 respectively, and a gradient height ( $z_G$ ) hourly mean wind speed of  $50 \text{ ms}^{-1}$ . See Equations (C.3) to (C.10):

$$V_{\text{tr}, z, T=3\,600\text{ s}} = \frac{u^*}{0,4} \left\{ \ln\left(\frac{z}{z_0}\right) + 5,75\left(\frac{z}{z_G}\right) - 1,88\left(\frac{z}{z_G}\right)^2 - 1,33\left(\frac{z}{z_G}\right)^3 + 0,25\left(\frac{z}{z_G}\right)^4 \right\} \quad (\text{C.3})$$

$$z_G = \frac{u^*}{6f} \quad (\text{C.4})$$

$$\sigma_v = \frac{7,5\eta u_* \left[ 0,538 + 0,09 \ln \left( \frac{z}{z_0} \right) \right] \eta^{16}}{1 + 0,156 \ln \left( \frac{u_*}{f z_0} \right)} \quad (\text{C.5})$$

$$\eta = 1 - \frac{6fz}{u_*} \quad (\text{C.6})$$

$$f = 2\Omega \sin \phi \quad (\text{C.7})$$

where

$\phi$  is the latitude,

$\Omega$  is angular velocity of the Earth's rotation ( $= 72,9 \times 10^{-6}$  radians/s),

$u_*$  is the frictional velocity  $\left( \sqrt{\frac{\text{surface friction shear stress}}{\text{atmospheric air density}}} \right)$ .

$$I_{v,z} = \frac{\sigma_{v,z}}{V_{z,T=3\,600\text{ s}}} \quad (\text{C.8})$$

(i.e., turbulence intensity based on hourly mean wind speed at a specific location of height and terrain roughness)

$$V_{tr,z,T=3\text{ s}} = V_{z,T=3\,600\text{ s}} (1 + 3,0 I_{v,z}) \quad (\text{C.9})$$

$$V_{tr,z,T=600\text{ s}} = V_{z,T=3\,600\text{ s}} (1 + 0,28 I_{v,z}) \quad (\text{C.10})$$

Values of  $z_0$  for various terrain roughness conditions are given in Figure C.1.

Some evaluations of the terrain roughness and height exposure factors and turbulence intensities for synoptic storm profiles are given in Table C.1 for a latitude of  $40^\circ$ . The Deaves and Harris equations are not valid for latitudes approaching zero degrees and would not normally be used for values of  $\phi < 20^\circ$ . The evaluations in Table C.1 differ slightly from those defined in C.1 because the Deaves and Harris equations are based on a mean averaging time of  $T = 3\,600$  s, as used in some countries. Hence the evaluation of the mean wind speed profiles have been carried out for  $T = 3\,600$  s, then converted to the peak and mean reference times used in this International Standard of  $T = 3$  s and  $T = 600$  s, respectively. Further, because of the calculation method used, the terrain roughness and height exposure factors in Table C.1 are all given as a ratio with the peak reference wind speed,  $V_{\text{ref}}$ , which is for  $T = 3$  s at  $z = 10$  m in open country terrain, as given in Equations (C.11), (C.12) and (C.13):

$$k_{tr,z} = \frac{V_{tr,z}}{V_{\text{ref}}} \quad (\text{C.11})$$

$$k_{tr,z,m} = \frac{V_{tr,z,m}}{V_{\text{ref}}} \quad (\text{C.12})$$

$$k_{tr,z,T=3\,600\text{ s}} = \frac{V_{tr,z,T=3\,600\text{ s}}}{V_{\text{ref}}} \quad (\text{C.13})$$

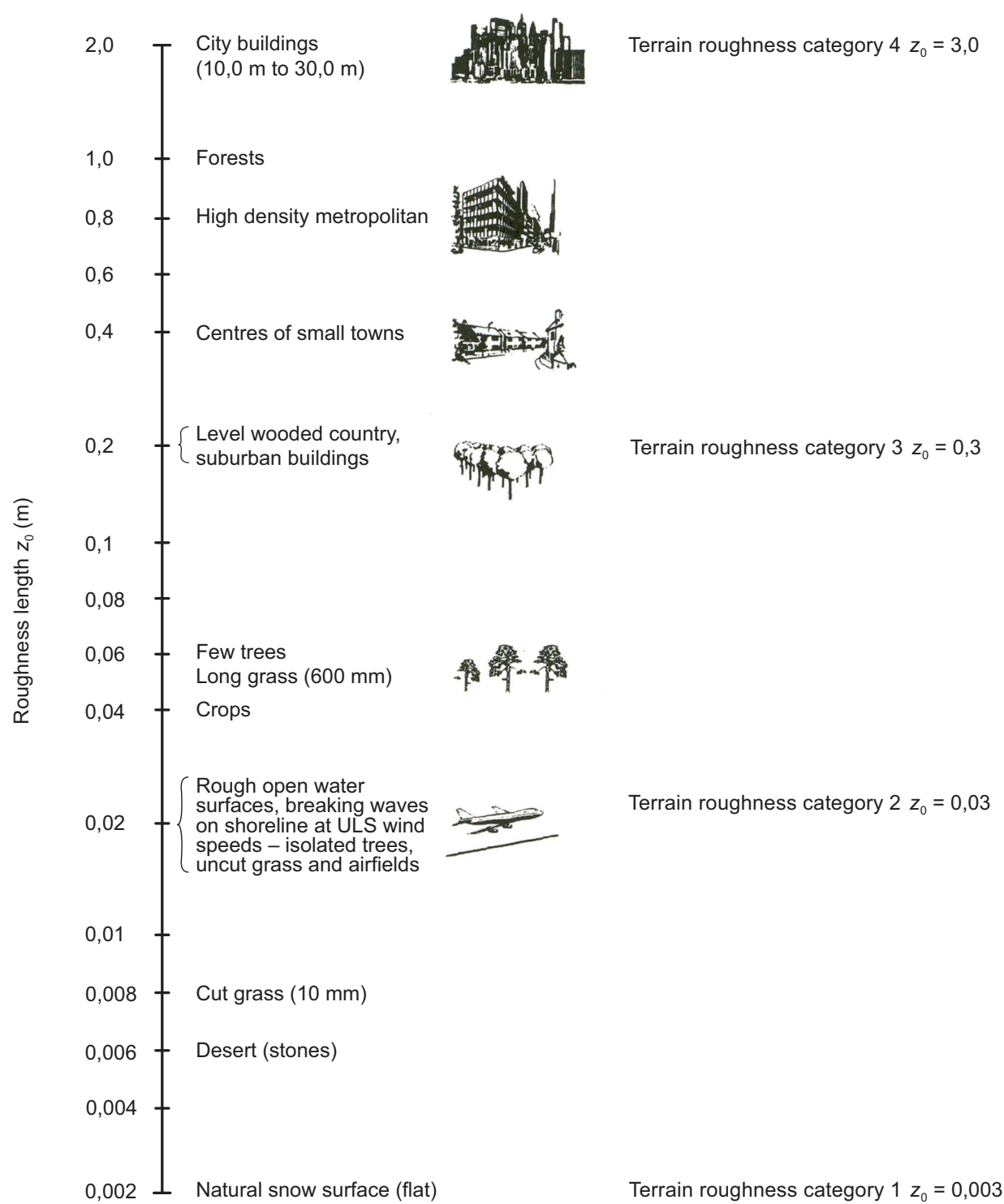
Where, as specified in this International Standard any parameter without a definition for averaging time,  $T$ , is a peak value for  $T = 3$  s.

If the mean terrain roughness and height exposure factors are required, they can be obtained from the ratio of the factors in Table C.1, with either the  $T = 600$  s or  $T = 3\,600$  s factor at  $z = 10$  m in open country terrain, as appropriate.

The logarithmic law profiles can be approximated by power law profiles with only the one variable for terrain roughness category being the power law exponent,  $\beta$ , as given in Equation (C.14):

$$V_{tr,z} = V_{tr,z=10\text{ m}} \left( \frac{z}{10} \right)^{\beta} \text{ and } V_{tr,z,m} = V_{tr,z=10\text{ m},m} \left( \frac{z}{10} \right)^{\beta_m} \quad (\text{C.14})$$

Values for  $\beta$  and  $\beta_m$  have been fitted between 10 m and 200 m and are given in Table C.1.



**Key**  
 $z_0$  roughness length, expressed in metres

Figure C.1 — Description of terrain roughness lengths,  $z_0$

**Table C.1 — Terrain roughness and height exposure factors,  $k_{tr, z}$  and  $k_{tr, z, m}$ , and turbulence intensity profiles for four terrain roughness categories over flat terrain for synoptic storms for latitude  $\phi = 40^\circ$**

| Terrain roughness category                                                                                                                                                                                                                                                                                                   | Characteristics    |                             |                                  |                                  |                                                 |
|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------|-----------------------------|----------------------------------|----------------------------------|-------------------------------------------------|
|                                                                                                                                                                                                                                                                                                                              | Height<br>$z$<br>m | $k_{tr, z}$<br>( $T = 3$ s) | $k_{tr, z, m}$<br>( $T = 600$ s) | $k_{tr, z}$<br>( $T = 3\,600$ s) | Turbulence intensity<br>$I_{V, z, T = 3\,600$ s |
| 1. Open sea flat surface<br>$z_0 = 0,003$ m                                                                                                                                                                                                                                                                                  | 3                  | 0,97                        | 0,70                             | 0,67                             | 0,148                                           |
|                                                                                                                                                                                                                                                                                                                              | 5                  | 1,03                        | 0,75                             | 0,72                             | 0,142                                           |
|                                                                                                                                                                                                                                                                                                                              | 10                 | 1,11                        | 0,82                             | 0,79                             | 0,135                                           |
|                                                                                                                                                                                                                                                                                                                              | 20                 | 1,19                        | 0,89                             | 0,86                             | 0,127                                           |
|                                                                                                                                                                                                                                                                                                                              | 50                 | 1,28                        | 0,99                             | 0,96                             | 0,112                                           |
|                                                                                                                                                                                                                                                                                                                              | 100                | 1,33                        | 1,07                             | 1,04                             | 0,095                                           |
|                                                                                                                                                                                                                                                                                                                              | 200                | 1,39                        | 1,15                             | 1,13                             | 0,076                                           |
|                                                                                                                                                                                                                                                                                                                              | 500                | 1,49                        | 1,31                             | 1,29                             | 0,052                                           |
|                                                                                                                                                                                                                                                                                                                              | 1 000              | 1,58                        | 1,46                             | 1,44                             | 0,032                                           |
|                                                                                                                                                                                                                                                                                                                              | $\beta$            | —                           | $\beta = 0,074$                  | $\beta_m = 0,113$                | $\beta_T = 3\,600 = 0,120$                      |
| 2. Open country/<br>open sea in ultimate<br>limit state conditions<br>$z_0 = 0,03$ m                                                                                                                                                                                                                                         | 3                  | 0,83                        | 0,55                             | 0,52                             | 0,203                                           |
|                                                                                                                                                                                                                                                                                                                              | 5                  | 0,90                        | 0,61                             | 0,58                             | 0,191                                           |
|                                                                                                                                                                                                                                                                                                                              | 10                 | 1,00                        | 0,69                             | 0,655                            | 0,178                                           |
|                                                                                                                                                                                                                                                                                                                              | 20                 | 1,10                        | 0,77                             | 0,73                             | 0,165                                           |
|                                                                                                                                                                                                                                                                                                                              | 50                 | 1,21                        | 0,88                             | 0,85                             | 0,147                                           |
|                                                                                                                                                                                                                                                                                                                              | 100                | 1,29                        | 0,97                             | 0,94                             | 0,128                                           |
|                                                                                                                                                                                                                                                                                                                              | 200                | 1,36                        | 1,07                             | 1,04                             | 0,106                                           |
|                                                                                                                                                                                                                                                                                                                              | 500                | 1,48                        | 1,23                             | 1,21                             | 0,074                                           |
|                                                                                                                                                                                                                                                                                                                              | 1 000              | 1,58                        | 1,40                             | 1,38                             | 0,048                                           |
|                                                                                                                                                                                                                                                                                                                              | $\beta$            | —                           | $\beta = 0,103$                  | $\beta_m = 0,147$                | $\beta_T = 3\,600 = 0,154$                      |
| 3. Suburban<br>$z_0 = 0,3$ m                                                                                                                                                                                                                                                                                                 | 3                  | 0,84                        | —                                | —                                | —                                               |
|                                                                                                                                                                                                                                                                                                                              | 5                  | 0,84                        | 0,40                             | 0,37                             | 0,311                                           |
|                                                                                                                                                                                                                                                                                                                              | 10                 | 0,84                        | 0,50                             | 0,47                             | 0,269                                           |
|                                                                                                                                                                                                                                                                                                                              | 20                 | 0,96                        | 0,60                             | 0,56                             | 0,239                                           |
|                                                                                                                                                                                                                                                                                                                              | 50                 | 1,12                        | 0,73                             | 0,69                             | 0,208                                           |
|                                                                                                                                                                                                                                                                                                                              | 100                | 1,23                        | 0,83                             | 0,79                             | 0,184                                           |
|                                                                                                                                                                                                                                                                                                                              | 200                | 1,33                        | 0,95                             | 0,91                             | 0,156                                           |
|                                                                                                                                                                                                                                                                                                                              | 500                | 1,47                        | 1,13                             | 1,10                             | 0,111                                           |
|                                                                                                                                                                                                                                                                                                                              | 1 000              | 1,58                        | 1,32                             | 1,29                             | 0,075                                           |
|                                                                                                                                                                                                                                                                                                                              | $\beta$            | —                           | $\beta = 0,152$                  | $\beta_m = 0,214$                | $\beta_T = 3\,600 = 0,220$                      |
| 4. Urban<br>$z_0 = 3,0$ m                                                                                                                                                                                                                                                                                                    | 3                  | 0,59                        | —                                | —                                | —                                               |
|                                                                                                                                                                                                                                                                                                                              | 5                  | 0,59                        | —                                | —                                | —                                               |
|                                                                                                                                                                                                                                                                                                                              | 10                 | 0,59                        | 0,23                             | 0,20                             | 0,677                                           |
|                                                                                                                                                                                                                                                                                                                              | 20                 | 0,74                        | 0,35                             | 0,31                             | 0,473                                           |
|                                                                                                                                                                                                                                                                                                                              | 50                 | 0,95                        | 0,51                             | 0,46                             | 0,355                                           |
|                                                                                                                                                                                                                                                                                                                              | 100                | 1,12                        | 0,64                             | 0,59                             | 0,302                                           |
|                                                                                                                                                                                                                                                                                                                              | 200                | 1,27                        | 0,77                             | 0,72                             | 0,254                                           |
|                                                                                                                                                                                                                                                                                                                              | 500                | 1,46                        | 0,99                             | 0,94                             | 0,184                                           |
|                                                                                                                                                                                                                                                                                                                              | 1 000              | 1,59                        | 1,20                             | 1,16                             | 0,126                                           |
|                                                                                                                                                                                                                                                                                                                              | $\beta$            | —                           | $\beta = 0,256$                  | $\beta_m = 0,403$                | $\beta_T = 3\,600 = 0,428$                      |
| NOTE Values in terrain roughness categories 3 and 4 below 5 m and 10 m have been left conservatively constant or blank as these heights are close to or below the actual roughness elements in these categories. It is necessary to determine the effects of shielding from wind tunnel measurements of relevant references. |                    |                             |                                  |                                  |                                                 |

### C.2.2 Tropical cyclone storm profiles

Research into wind speed profiles for tropical cyclones (typhoons or hurricanes) has produced a wide scatter of results over the last few decades. A recent review, in Reference [9], has recommended that there is not enough evidence to use other than logarithmic-law (or power-law) profiles near the ground (up to 500 to 1 000 m). Hence, it is recommended that terrain roughness category 2 given in Table C.1 be used for tropical cyclones.

Measurements by References [6] and [7] and studies by Reference [8] have shown episodes of relatively high values of turbulence intensity embedded in tropical cyclone records. In particular, the vertical components relative to the longitudinal components are significantly higher than for a neutral boundary layer flow. During these episodes there is evidence that the increased energy occurs in the inertial subrange, hence the averaging time factor given in Table B.1 is not applicable to these episodes.

### C.2.3 Thunderstorm profiles

Whilst the general characteristics of thunderstorms and downbursts are well known, the measurements of profile data are very sparse. Measurements and some unpublished data have enabled a preliminary envelope of peak wind speeds to be developed for this International Standard, but more information, such as that currently being collected at Texas Tech University<sup>1)</sup>, will be important to continuing validation. An enveloping profile of peak wind speeds for thunderstorms is given using Equation (C.15):

$$k_{tr, z, peak} = 0,821 + 7,55 \times 10^{-4} z - 6,75 \times 10^{-6} z^2 + 1,06 \times 10^{-8} z^3 - 4,97 \times 10^{-12} z^4 + 0,079 \ln(z - 1,4) \quad (C.15)$$

Information on effective turbulence intensity in severe thunderstorm downdrafts is given in Reference [10].

Some evaluation of this enveloping profile is given in Table C.2. No guidance can be given with respect to turbulence intensities in thunderstorms at this stage; only the synoptic storm turbulence intensities for the appropriate terrain are available at present.

**Table C.2 — Terrain roughness and height exposure factors for peak wind speeds,  $k_{tr, z}$ , for three terrain roughness categories for thunderstorms**

| Terrain roughness category                   | Height<br>$z$<br>m | $k_{tr, z}$ |
|----------------------------------------------|--------------------|-------------|
| 1, 2 and 3<br>Open sea, country and suburban | 3                  | 0,86        |
|                                              | 5                  | 0,93        |
|                                              | 10                 | 1,00        |
|                                              | 20                 | 1,06        |
|                                              | 50                 | 1,15        |
|                                              | 100                | 1,20        |
|                                              | 200                | 1,20        |
|                                              | 500                | 1,02        |
|                                              | 1 000              | 1,00        |

1) Wind Science and Engineering Research Centre, Texas Tech University, Lubbock, Texas, USA.

For thunderstorm environments only the peak wind speeds are relevant for the determination of design wind speeds. Use of peak wind speeds for the determination of design loads is recommended, although an artificial mean wind speed approach could be used for dynamic analysis. It is noted that in many cases for tall structures the thunderstorm data might only control the ultimate limit state design loads and at the serviceability levels the synoptic storm winds are likely to control. In all mixed storm environments it is important that the extreme wind speed analyses be done for data separated into each storm type.

### C.3 Turbulence spectrum and length scale

#### C.3.1 Turbulence spectrum

The most commonly used expression for the longitudinal spectrum of turbulence is due to von Karman, which is also generally used as an approximation in terms of wind speed and is given in Equation (C.16):

$$\frac{f S_v}{\sigma_v^2} = \frac{4 \left( \frac{f L_v}{V_m} \right)}{\left\{ 1 + 70,8 \left( \frac{f L_v}{V_m} \right)^2 \right\}^{\frac{5}{6}}} \quad (\text{C.16})$$

where

$f$  is the frequency;

$S_v$  is the longitudinal spectrum of turbulence in terms of wind speed;

$L_v$  is the longitudinal integral length scale;

$V_m$  is mean wind speed;

$\sigma_v$  is the standard deviation of wind speed.

#### C.3.2 Integral length scale of turbulence

The determination of integral length scale of turbulence is very complex, but for wind engineering calculations it is possible to conveniently approximate it using Equation (C.17):

$$L_v = 100 \left( \frac{z}{30} \right)^{0,5} \quad (\text{C.17})$$

where

$L_v$  is the integral length scale, in metres;

$z$  is the height above ground, in metres.

### C.4 Change in terrain roughness effects

Adjustments to height exposure factors and terrain roughness due to changes in terrain roughness in immediate approach fetches can be approximated by a linear weighting of the height exposure factors and terrain roughness over a defined averaging distance for a given height, as given in Table C.3 and Table C.4