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ESDU 72026

Strong winds in the atmospheric boundary layer Part 1: hourly-mean wind speeds

**Associated software: VIEWpac E0108
(Data Item ESDU 01008)**

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THE PREPARATION OF THIS DATA ITEM

The work on this particular Data Item which supersedes ESDU 72026, was monitored and guided by the Wind Engineering Panel. This Panel, which took over the work on wind engineering previously monitored by the Fluid Mechanics Steering Group, first met in 1979 and now has the following membership:

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STRONG WINDS IN THE ATMOSPHERIC BOUNDARY LAYER. PART I: HOURLY-MEAN WIND SPEEDS

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STRONG WINDS IN THE ATMOSPHERIC BOUNDARY LAYER.

Part I: hourly-mean wind speeds

1. NOTATION AND UNITS

		SI Unit
a, a_q	reciprocal of dispersion parameters in Fisher-Tippett (Type 1) extreme value distribution function, based on analysis of V and $q = \frac{1}{2} \rho V^2$ respectively (see Section A3, Appendix A)	$(\text{m/s})^{-1}$ and $(\text{kN/m}^2)^{-1}$
d	displacement height of zero-plane above ground	m
F	value of fetch x of uniform terrain upwind of site necessary for equilibrium boundary layer to exist at site ($F \approx 100$ km)	m
f	Coriolis parameter, $2\Omega \sin \phi$ (see Section A1, Appendix A)	rad/s
H	general obstruction height of surrounding obstacles	m
h	gradient height or equilibrium boundary layer height above which V_z is independent of underlying terrain	m
h_i	height of internal layer at fetch x (see Sketch 3.1)	m
K_L	factor accounting for topographical effects on wind speed (Section 10)	
K_N	probability factor accounting for effect on extreme wind speed of values of P_N and N different from standard values (see Section 5)	
$\left. \begin{matrix} K_s \\ K_{s*} \end{matrix} \right\}$	terrain roughness factors relating wind speeds at nearby sites with different terrains; given respectively by $V_{10}/V_{10,r}$ and u_*/u_{*r} (see Section 7)	
K_x	fetch factor accounting for distance of site downwind from sudden change in terrain roughness; V_{zx}/V_z (see Section 9)	
$\left. \begin{matrix} K_z \\ K_{z*} \end{matrix} \right\}$	height factors accounting for effect of z on V_z and given respectively by V_z/V_{10} and V_z/u_* (see Section 8)	
K_θ	directional factor giving sectorial distribution of extreme wind speed at site assuming uniform terrain in all directions, $K_\theta = V_\theta\{P_N\}/V\{P_N\}$ (see Section 4.3)	
N	exposure period or anticipated structure life	years
P_1	probability of an extreme wind speed being exceeded in any one year; $P_1 = 1/T$	

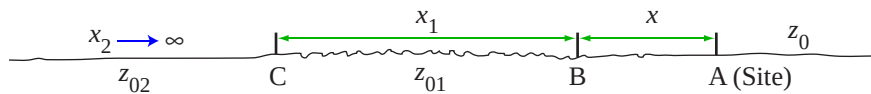
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P_N	probability of an extreme wind speed being equalled or exceeded once in N years	
P_{Nr}	probability of reference wind speed of return period T_r being equalled or exceeded in N years	
q	dynamic pressure, $\frac{1}{2} \rho V^2$	kN/m ²
R	roughness-change parameter; $ \ln(z_0/z_{01}) /(u_*/(fz_0))^n$ where $n = 0.23$ and 0.14 for smooth-to-rougher terrain and rough-to-smoother terrain respectively	
T	return period; average period between consecutive occurrences of particular extreme value	years
U, U_q	mode parameters in Fisher-Tippett (Type 1) extreme value distribution function based on analysis of V and $q = \frac{1}{2} \rho V^2$ respectively (see Section A3, Appendix A)	m/s, kN/m ²
u_*	friction (or shear) velocity at site in question; $(\tau_0/\rho)^{0.5}$	m/s
V	wind speed at height z ; mean wind speed profile in equilibrium conditions over roughness z_0 in Sections 9 and A2	m/s
V_h	gradient wind speed, V_z at $z = h$	m/s
V_z	hourly-mean wind speed; wind speed averaged over 1 hour at height z above site in question assuming site terrain roughness extends uniformly upwind for at least 100 km (<i>i.e.</i> equilibrium boundary-layer conditions)	m/s
V_{zx}	hourly-mean wind speed at height z above site in question with change in terrain roughness a distance x upwind from site (see Sketch 3.1)	m/s
V_{10}	V_z for $z = 10$ m	m/s
$V\{P_N\}$	extreme wind speed from all directions at given height with given risk of exceedance P_N	m/s
$V_\theta\{P_N\}$	extreme wind speed in particular direction θ , having same overall risk of exceedance (distributed uniformly by direction) as $V\{P_N\}$	m/s
x	distance (fetch) that uniform terrain roughness extends upwind of site in question (see Sketch 3.1)	m
x_1	patch length of uniform terrain between first and second step changes in terrain roughness upwind of site in question (see Sketch 9.4)	m
z	height measured from zero-plane displacement (see Sketch 6.1)	m
z_0	surface (terrain) roughness parameter (Section 6.1 and Table 13.1)	m
θ	direction, measured from north, from which wind is blowing	degree
κ_{10}	surface drag coefficient; $\kappa_{10} = \tau_0/(\rho V_{10}^2) = (u_*/V_{10})^2$	

λ	density ratio of ground obstructions; ratio of plan area of ground obstacles to total ground area containing obstacles	
ρ	air density	kg/m ³
τ_0	average shear stress at surface	kN/m ²
ϕ	local angle of latitude	degree
Ω	angular rate of rotation of Earth; 72.9×10^{-6} rad/s	rad/s

Subscripts

1, 2	relate respectively to conditions upwind of first and second step changes in terrain roughness upwind from site in question (see Sketch 1.1)
A, B, C	denote respectively values at site in question (A), at first step change (B), and at second step change (C) in terrain roughness upwind of site (see Sketch 1.1)



Sketch 1.1

r	relates to reference, or standard, conditions
x	denotes value at location x downwind of step change in terrain roughness and indicates non-equilibrium boundary layer conditions
z	relates to value at height z

2. PURPOSE, SCOPE AND APPLICABILITY

Over the last decade the behaviour and characteristics of the atmospheric wind in the lower layers of the atmosphere have become increasingly important in relation to design requirements over a broad range of engineering problems. In particular, the current trends of building design and new methods of construction have led to a need to establish, at an early stage of design, the magnitude of wind loads that can be expected during the lifespan of a structure. As the knowledge of force and pressure coefficient data increases, both in terms of scope and accuracy, it becomes increasingly important to establish the magnitude of the design wind speed as precisely as possible. To obtain this information a realistic model of the atmospheric wind is required not only for design calculations but also for simulation techniques used in wind tunnels. In addition, a knowledge of the characteristics of the atmospheric wind near the ground has become increasingly important in the aerospace field but particularly in relation to V/STOL and conventional aircraft flying near the ground during the take-off and landing phases under automatic control.

2.1 Purpose and Scope of this Data Item

The purpose of the Data Item is to provide a method of estimating hourly-mean wind speeds in the neutral* atmospheric boundary layer near the ground. The information presented is for strong winds* ($V_{10} > 10$ m/s) produced by cyclonic storms (*i.e.* flow around a centre of low pressure) implying a neutrally-stable* atmosphere for which several simplifying assumptions make it possible to present generalised methods. These methods take into account the following main parameters.

- (i) Height above the ground at the site.
- (ii) The surface roughness of the local terrain at the site.
- (iii) Changes in terrain roughness upwind of the site.
- (iv) The probability of the wind speed being exceeded.

Additionally, some guidance is provided on the effects produced by local topography such as nearby hills, slopes and valleys.

2.1.1 Principal changes from Item No. 72026

This Data Item supersedes that part of Item No. 72026 dealing with hourly-mean wind speeds. The principal changes incorporated in this Item are as follows.

- (i) A more rigorous mathematical model has been used to describe the atmospheric boundary layer (see Appendix A) where the wind has blown over a sufficient fetch of uniform level terrain for dynamic equilibrium to have been established. (In this situation energy extracted from the flow exactly balances that absorbed by the generation of drag forces at the surface; for *true* equilibrium the fetch needs to be several hundreds of kilometres.) In many cases, the new model predicts lower values of design wind speed than Item No. 72026.
- (ii) A realistic method is included to allow for non-equilibrium boundary-layer effects produced by upwind fetches of terrain that have a different surface roughness from that at the site in question.
- (iii) The extreme wind speed map now provided for the United Kingdom is based on an analysis including individual storm data (see Section A3 in Appendix A) and information is provided giving an indication of the directional distribution of extreme wind speeds in the UK. Extreme wind speeds from this analysis are lower than those previously recommended for the same probability of occurrence for the reasons discussed in Section A3 of Appendix A.

It is inevitable that the values of wind speed calculated using this Item will be compared with values calculated from other design guides. The engineer will need to consider whether he can safely use the lower values of wind speed that this Item may give (and correspondingly lower values of load) in conjunction with current load factors. This raises the matter of load factors in the whole design and in particular the apportionment between the partial factors considered to apply to loads and those considered to apply to resistance and to other uncertainties in the design. This important aspect can be related in part to the probability or risk of exceedance used in establishing the extreme wind speed for design; the relation between this risk and partial factors is discussed in Section B1 of Appendix B and further highlighted in Section 4.1.

* In strong winds ($V_{10} > 10$ m/s) there is so much mechanical stirring of the atmosphere that convective currents are eliminated and masses of air that are displaced upwards tend to remain in their displaced positions. In such circumstances the atmosphere is said to possess neutral stability. In a neutral atmosphere the rate at which the air temperature decreases with increasing height is about 1°C per 100 m.

2.2 How to Use the Data Item; Related Computer Program

The bulk of this Item describes the data and methods (and their derivation) on which the calculation procedures are based. The Calculation Sheets (Tables 13.2 and 13.3) provide a simplified means of applying these methods and contain step-by-step procedures for estimating a value, or range of values, of hourly-mean wind speed for a given set of conditions. The Calculation Sheets are self-explanatory but the user is recommended to read the background notes in Sections 3 to 10. Background notes on the physical processes involved and the means by which the data in the Item have been derived are given in Appendix A.

The simplified procedures given in this Data Item accounting for terrain with roughness changes have been derived (as described in Appendix A) for use in hand calculations. The full methods have been incorporated into a computer program, VIEWpac E0108, (described in ESDU 01008²⁵) which calculates both mean wind speeds and gusts (as well as turbulence intensities, length scales and spectra) for multiple roughness changes over flat or hilly terrain. This program is in the form of a Visual Basic module running in Microsoft Excel. It is recommended that the program is used where more than one roughness change and/or topographic effects are to be accounted for.

2.3 Application to Wind Loading on Buildings and Structures

The occurrence of a particular value of wind speed at a particular site and time is not something that can be predicted; it is a random event and produces an equally random wind loading effect. However, by analysing data collected over the long term, it is possible to associate a given magnitude of wind speed with a probability of that value being exceeded in a given period; this in turn is linked to the magnitude of the loading effect produced by the wind. For simple, stiff structures the assumption can be made that there are no dynamic effects due to vibration of the structure and an appropriate maximum wind speed can be used to calculate the wind loading by a “discrete-gust” method (Section 2.3.1). When the structure is less stiff and more susceptible to vibration, or is very large, the statistical relationships between wind speed fluctuations from the mean in time and space become important; in this case the “time-series” approach, *i.e.* that involving spectral or correlation methods (Section 2.3.2) is more appropriate.

2.3.1 The discrete-gust loading approach

The discrete-gust method is applicable to structures which are sufficiently stiff for wind effects to be determined by static methods and small enough that the assumption is valid that the wind loading is determined by a “discrete-gust”, averaged over t seconds, which completely envelops the structure or, if only part of the structure is under consideration, a component thereof.

The significance of this requirement is that maximum wind speeds averaged over a few seconds do not necessarily occur simultaneously at all positions on the structure unless the structure is completely enveloped by the gust (*i.e.* wind speeds, for a given averaging time, are not fully correlated over the face of a structure). The use of this approach in design calculations may lead to an overestimate of the quasi-static loading on structures which are either very high (*e.g.* tall buildings) or very wide (*e.g.* bridges) in the across-wind direction. The correct procedure in these circumstances would be to take an appropriate space average of the gust which requires information on the correlation of such gusts over distances in the lateral and vertical directions. There is insufficient information available for this average to be calculated except in a few special cases. Instead, an *ad hoc* procedure is often used in which a space average is obtained by averaging the gust at a point over a longer time interval (the longer the averaging time the greater is the spatial extent of the gust and the lower is the gust velocity).

Data relating to t -second gusts are given in Reference 5.

In this approach a further fundamental assumption is that the probability distribution (which represents the

risk of exceeding particular values) of the wind loading force and of the incident wind are the same. As discussed in References 3 and 4 this is not usually true since the aerodynamic and meteorological mechanisms producing random fluctuations in local pressure are different. A preferred method in existence^{3,4} is to evaluate (by wind-tunnel testing) the probability density distribution of the time-dependent pressure coefficient independently and then to evaluate the joint probability density of the resulting wind force or pressure as the product of this distribution and that of the incident wind. This method, when incorporated into design methods, will require a knowledge of the hourly-mean wind speed characteristics given in this Item.

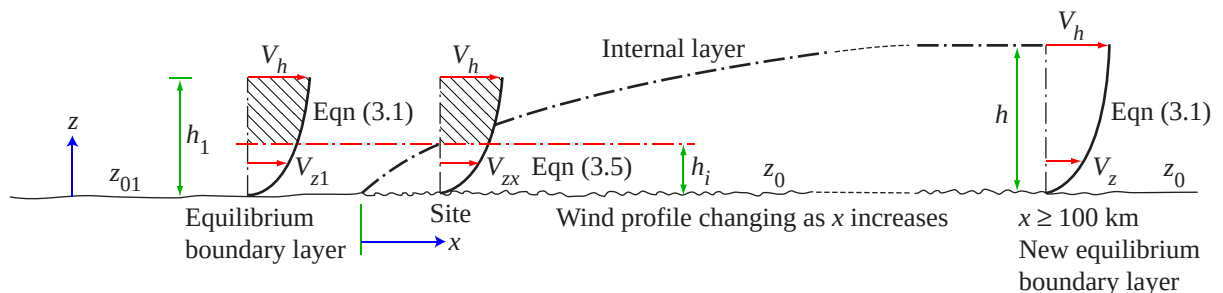
2.3.2 The time-series approach

For structures which are sufficiently large, or for structures which are less stiff, the discrete-gust approach is unrealistic and the time-series approach is then more appropriate. This approach is based on estimating a mean loading due to a hourly-mean wind speed, V_z , onto which is superimposed a component to account for fluctuations in the wind speed about the hourly mean (turbulence). It uses statistical relationships to account for correlation effects between turbulence components at different points on a structure in a more realistic way than is possible using the discrete-gust approach and also accounts for the time-dependent nature of turbulence.

For less stiff structures a complete dynamic calculation should be made (using such methods as are given in Reference 2) primarily because the pulsating nature of turbulence can give rise to magnified stress levels through motions of the structure. This treatment requires a knowledge of extreme hourly-mean wind speeds and a detailed knowledge of the structure of atmospheric turbulence. The characteristics of the hourly-mean wind speed are dealt with in this Data Item. The properties of atmospheric turbulence are dealt with in Data Item Nos. 74030, 85020 and 86010.

3. THE FACTORS AFFECTING WIND SPEED AND THEIR CALCULATION

The mechanisms that produce and influence the nature of the wind near the surface of the Earth are described in Appendix A. The net result is that the wind at heights well above the Earth's surface is directed along lines of equal pressure. This is called the gradient wind and its magnitude is unaffected by the detailed roughness of the Earth's surface such as mountains, valleys, towns, trees and other obstacles. At the surface of the Earth horizontal drag forces, induced by ground obstacles, are exerted on the wind flow causing it to slow down. This force decreases with increasing height above the ground and becomes negligible at the gradient height (h) where the wind speed first reaches the gradient wind value. For strong winds h can vary between about 500 m and 3000 m above the ground depending on terrain roughness and the strength of the wind. The region between the ground and the gradient height is known as the atmospheric boundary layer in which the wind speed progressively increases with height as illustrated in Sketch 3.1.



Sketch 3.1 Developing wind profile

In practice, providing the wind has blown over a fetch of at least 100 km of uniform terrain the boundary layer is in equilibrium with the underlying surface *i.e.*, the variation of wind speed with height (the wind profile) does not change as the fetch (x) of upwind uniform terrain increases. Immediately downwind of a change in terrain roughness, such as at the edge of a town, a new internal layer begins to grow as illustrated in Sketch 3.1. Within this new layer the flow is not in equilibrium and the wind profile changes as x increases. Above the internal layer it can be assumed for all practical purposes that the wind profile is the same as that immediately upwind of the roughness change, at the same level.

The wind speed at a point in the atmospheric boundary layer is thus dependent on the gradient wind speed which in turn depends on geographical location. However, because the gradient wind speed cannot be measured easily it cannot, in general, be used as a basis for wind speed estimation at lower heights. For this reason wind speeds measured near the ground are used as reference values but it is then necessary to make additional corrections for the effect due to local variations in surface roughness (and their fetch) from the reference conditions.

The parameters which affect the determination of the strong-wind speed in the atmospheric boundary layer are as follows.

- (i) Geographical location; the reference wind speed.
- (ii) The height of the point above the ground.
- (iii) The surface roughness at the site in question.
- (iv) Surface roughness changes upwind of the site in question.
- (v) The surrounding topography (hills, slopes, *etc.*).

The following time factors are also important.

- (vi) The average return period (T) of the extreme value of wind speed. This is the average interval between occurrences of that wind speed.

Also of importance, in the case of actual design values, is the exposure period, N years, during which there will be a probability or risk, P_N , of exceeding the extreme value with a T -year return period. Note that N and T are not necessarily equal but together they determine the level of risk, P_N (see Equation (5.1)).

- (vii) The time over which a maximum wind speed is averaged.

The data in this Item relate to the hourly-mean wind speed, *i.e.* the wind speed averaged over 1 hour. The properties of gusts averaged over much shorter periods (such as a few seconds) are dealt with in Reference 5.

3.1 The Calculation of Hourly-mean Wind Speed

In the case of wind loading the wind speed required is usually the extreme hourly-mean wind speed at a certain height, or a wind profile over a height range, which has a particular probability, P_N , of being equalled or exceeded once in a given period, N years, corresponding to the intended life span of the structure. The general equations for solving this problem are summarised by Equations (3.1) to (3.5) in which the K -factors account for variations in the various statistical and site parameters. These factors, summarised in Table 3.1, are described in Sections 4 to 10 and derived in Appendix A. The overall calculation procedure is given by the Calculation Sheets (Tables 13.2 and 13.3).

In the simplest case the general description of the terrain roughness upwind from the site in question is assumed to be the same for at least 100 km and the boundary layer is in equilibrium (see Section 3). The wind speed at the site is then given by

$$V_z = u_{*r} \frac{K_N}{K_{Nr}} K_\theta K_{s*} K_{z*} K_L \quad (3.1)$$

where
$$u_{*r} = V_r / K_{z*r} \quad (3.2)$$

or alternatively by
$$V_z = V_{10,r} \frac{K_N}{K_{Nr}} K_\theta K_s K_z K_L \quad (3.3)$$

where
$$V_{10,r} = V_r / K_{zr}. \quad (3.4)$$

In Equations (3.2) to (3.4) V_r (or $V_{10,r}$) is a reference wind speed, such as taken from a map of extreme values like Figures 1a and 1b (corresponding to reference conditions z_r , z_{0r} , P_{Nr} and N_r) and u_{*r} is the corresponding friction velocity (see Section A1 of the Appendix) given by Equation (3.2). The various K factors are described in Table 3.1 and account for departures at the site in question from the reference wind speed conditions. In the general case, when the terrain roughness is not uniform upwind of the site in question, values of u_* are required in the method accounting for non-equilibrium effects; in this situation it is more convenient to use Equation (3.1) than Equation (3.3) and this form is used in the Calculation Sheets (Tables 13.2 and 13.3).

TABLE 3.1

	Purpose	Section	Figure or Table	Equation
V_{zx}	Required value of wind speed at site in question, a distance x downwind of nearest step change in terrain roughness			(3.1) to (3.5)
V_r $V_{10, r}$	Reference wind speeds*, at height z_r and 10 m respectively, for reference terrain roughness† z_{0r}	4 4		
K_θ	Corrects for direction of wind	4.3	Table 4.1	
K_N K_{Nr}	Corrects for risk of exceedance and exposure period different from those applicable to the reference wind speed (with Fig. 1, $K_{Nr} = 1$)	5	Fig. 2	(5.2)
z_0	Surface roughness parameter dependent on nature of terrain	6.1	Table 13.1	
K_{s*} K_s	Correct for difference between reference terrain roughness z_{0r} and actual site roughness† z_0 ; $K_{s*} = u_*/u_{*r}$; $K_s = V_{10}/V_{10, r}$	7	Fig. 4 Fig. 5	(7.2) (7.4)
K_{z*} K_z	Correct† for effect of height over terrain roughness z_0 ; $K_{z*} = V_z/u_*$; $K_z = V_z/V_{10}$	8	Fig. 6 Fig. 7	(A1.8) (A1.10)
K_x	Corrects for effect of step change in terrain roughness a distance x upwind of site in question for $z \leq h_i$; $K_x = V_{zx}/V_z$	9	Fig. 8	(A2.2) (A2.3)
K_L	Corrects for effect of local topography	10	Fig. 9	

* Normally, map values of extreme wind speed can be assumed to be appropriate to an equilibrium boundary layer and $z = 10$ m. In some cases when values are taken from individual site records this will not be so and the data should be corrected to eliminate the effect of any upwind changes in terrain roughness.

† This ignores all step changes in terrain roughness upwind of the site in question.

In the practical situation there are usually significant nearby sudden (or step) changes in terrain roughness upwind of the site in question (for example, on a coastline or at the edge of a town). A new inner layer develops, as illustrated in Sketch 3.1, and inside this layer ($z \leq h_i$) the wind speed, V_{zx} , is dependent on x and is given by

$$V_{zx} = V_z K_x \quad (3.5)$$

where K_x (Figure 8) depends on z_0 , z_{01} , u_* and x . Above this inner layer ($z > h_i$), $V_{zx} = V_{z1}$.

The procedure dealing with one or more upwind step changes in terrain roughness is described in Section 9 and summarised in the Calculation Sheets (Tables 13.2 and 13.3). In this case it is necessary to determine (or assume) the direction giving the most severe wind condition (see Section 4.3) taking account of upwind changes in terrain in the appropriate direction.

4. REFERENCE WIND SPEED

In order to estimate a wind speed (or a wind speed profile) it is necessary to start with a reference value V_r which may or may not be appropriate to the actual site characteristics such as terrain roughness (represented by z_0) and height. Corrections for the actual site parameters are made through Equations (3.1), (3.3) and (3.5).

For design purposes, the reference wind speed is usually an extreme value obtained by applying a statistical analysis to maximum wind speed data from wind speed records at a particular site over a period of years at a particular height, usually 10 m. A brief description of this process is given in Section A3 of Appendix A. For some areas of the world, but by no means most, maps or values of extreme wind speeds are available. The particular case of the UK is covered in Section 4.1; data sources for other areas of the world are given in Section 4.2.

4.1 Extreme Wind Speeds in the United Kingdom

Values of $V_{10,r}$, and equivalent values of u_{*r} , with a return period $T = 50$ years are presented in Figures 1a and 1b. They apply for flat terrain with $z_{0r} = 0.03$ m but require an increment of approximately 10% for every 100 m that the general level of the terrain (averaged over a radius of several kilometres from the site) is above mean sea level. (This correction does not account for speed-up effects over hills which are a different phenomenon.)

The values of $V_{10,r}$ in Figure 1a are the result of applying an improved extreme value analysis to wind speed data from meteorological stations in the UK. The data have been derived as described in Section A3 of Appendix A and are adjusted to apply for a reference height $z = 10$ m and to open level country ($z_{0r} = 0.03$ m). The map includes large-scale topographical effects such as the shielding effect produced by the Welsh mountains on areas to the east but it does not include local topographical effects such as those due to nearby hills, valleys, escarpments, etc. For guidance on these latter aspects see Section 10.

The data presented in Figure 1b are values of the friction velocity, u_{*r} , which are equivalent to the values of $V_{10,r}$ in Figure 1a; they are related by Equation (A1.11) in Appendix A so that for $z_{0r} = 0.03$ m and $z = 10$ m, u_{*r} (Figure 1b) = 0.0689 $V_{10,r}$ (Figure 1a). When using the Calculation Sheets (Tables 13.2 and 13.3), and particularly when changes in terrain roughness upwind of the site need to be considered, it is more convenient to proceed with a knowledge of u_{*r} ; hence maps of extreme values of u_{*r} , such as Figure 1b for the UK, are, in general, a more convenient starting point.

The data in Figures 1a and 1b are extreme values with a return-period (T) of 50 years. In statistical terms (as derived in Section A3 of Appendix A) this means that for an exposure period (N) of 50 years there is a probability $P_N = 0.636$ that the actual maximum wind speed will equal or exceed the map value. These are the standard conditions currently used to estimate design wind loadings in the UK. However, it may be appropriate to use other probability levels (P_N) and/or other exposure periods (N) as the basis for design; for example the intended lifespan of a structure may be less than, or more than, 50 years and in the case of serviceability criteria it may be possible to tolerate higher risks of exceedance. Appropriate wind speeds can be estimated using the probability factor K_N described in Section 5.

In practice, as discussed in Section B1 of Appendix B, a value of $P_N = 0.636$ represents an apparently fairly high risk of the unfactored design value being exceeded. A more stringent probability for design purposes (adopted in other design codes) would be $P_N = 0.05$. This would represent a value of $K_N = 1.155$. However, it should be appreciated that decreasing the risk of exceedance from 0.636 to 0.05 represents applying an equivalent partial factor of about $(1.155)^2 = 1.333$ on the wind loading if the 0.636 risk of exceedance in a 50-year exposure period is retained. Because the new analysis gives more accurate and more reliable values there is a correspondingly higher confidence in the extreme values estimated and the need for further partial

factors on wind loading is then questionable, in respect to the basic wind speed.

The use of these data therefore demands a careful consideration on the part of the engineer. A further discussion on partial factors and their interaction with risk of exceedance is given in Section B1 of Appendix B.

4.2 Extreme Wind Speeds Outside the United Kingdom

Section B2 in Appendix B provides a list of sources of data for reference wind speeds outside the UK. However, this list is not definitive and, where appropriate, the national meteorological office of the country concerned should be consulted.

4.3 Wind Direction, the Factor K_θ

Due to the rotation of the Earth there is a variation in the mean wind direction between ground level and the gradient height, h . Theoretical estimates of this change in mean wind direction for middle latitudes give values of about 20° over flat plains and 30° over city centres. However, since in the lower 300 m the change in mean wind direction is only about 2° or 3° it is reasonable to assume that the mean wind direction does not vary in this height range.

Obviously, any particular extreme value of wind speed will be applicable to a particular direction. The direction giving the highest extreme will differ from site to site although in the UK this direction is predominantly from a sector centred on a bearing of about $240^\circ - 250^\circ$ from north. The wind loading on structures depends on the orientation of the structure to the wind. Some national standards recommend that the design value of wind speed be considered applicable from any direction since, in general, this information is not available.

More recently Cook²¹ has extended his analysis of independent storm data (on which Figure 1 is based, see Section A3 of Appendix A) to include a directional analysis in 30° sectors for 50 sites in the UK. The average results for these 50 sites of the sectorial extreme analysis are presented in Table 4.1. This gives values of a factor, K_θ , equal to the ratio of the extreme value in a particular sector ($V_\theta\{P_N\}$) to the extreme value for all directions ($V\{P_N\}$), both having the same overall risk of exceedance*, P_N , in an exposure period of N years. Values of K_θ for those sectors containing the highest extreme values are greater than unity for the reasons explained in Section A3 of Appendix A.

TABLE 4.1 Values of K_θ Giving Directional Extreme Value $V_\theta\{P_N\}$

Values are for an evenly distributed overall risk (P_N) selected for the all-direction extreme value.

Values typical of UK sites with uniform terrain in all directions. For intermediate directions, values of K_θ may be interpolated.

θ°	0	30	60	90	120	150	180	210	240	270	300	330
K_θ	0.81	0.76	0.76	0.77	0.76	0.83	0.89	0.97	1.05	1.04	0.95	0.86

It must be emphasised that the distribution of K_θ is typical only of uniform terrain in all directions. Where local topographical features such as hills or valleys occur, or where there are changes in upwind terrain roughness in particular directions, these effects must be allowed for separately. Section 10 provides some guidance on the effect of local topography and Section 9 describes the method allowing for terrain roughness changes.

* For further explanation see Section A3 of Appendix A.

5. THE PROBABILITY FACTOR K_N

The ratio K_N/K_{N_r} accounts for the effect of the required exposure period, N , and/or the risk of exceedence, P_N , being different from that applicable to the reference extreme wind speed; it is obtained statistically as explained in Section A3 of Appendix A. The probability that an extreme wind speed with a return period T will be exceeded in any one year is $P_1 = 1/T$; this is related to the probability, P_N , that the same wind speed value will be equalled or exceeded in N years by the expression

$$P_N = 1 - (1 - P_1)^N = 1 - \left(1 - \frac{1}{T}\right)^N. \quad (5.1)$$

For example, the wind speed which is exceeded (on average) once in a period of 50 years has a probability of $1/50 = 0.02$ of being exceeded in any one year; in a period of 50 years the probability of the same wind speed being exceeded is $1 - (0.98)^{50} = 0.636$. In the limit as $N = T \rightarrow \infty$, $P_N \rightarrow 1 - e^{-1}$.

The factor K_N (for convenience) is defined as the ratio of the extreme value of wind speed associated with probability P_N and exposure period N to the extreme value of wind speed with $P_N = 0.636$ and $N = 50$ years. It is shown in Section A3 of Appendix A that this factor can be expressed as

$$K_N = \frac{V\{P_N, N\}}{V\{P_N = 0.636, N = 50\}} = \left\{ \frac{a_q U_q + \ln N - \ln(-\ln(1 - P_N))}{a_q U_q + 3.902} \right\}^{1/2}. \quad (5.2)$$

For sites in the UK it is found¹⁸ that the mean value of $a_q U_q$ is 5 (with individual values varying between 4 and 7) which would also apply for other areas with a similar wind climate. The factor K_N , given by Equation (5.2) with $a_q U_q = 5$, is plotted in Figure 2.

In Equations (3.1) and (3.3), K_{N_r} is appropriate to the reference wind speed of stated return period T ; it is the value of K_N (Figure 2) taking (by definition) $N_r = 50$ years and the corresponding value of P_{N_r} given by Equation (5.1). For example, when using Figure 1, since $T = 50$ years and (by definition) $N_r = 50$ years, then from Equation (5.1), $P_{N_r} = 0.636$ and hence $K_{N_r} = 1$. Other reference wind speed data may have been derived for other values of T ; in that case Equation (5.1) will give the appropriate value of P_{N_r} corresponding to $N_r = 50$ years and K_{N_r} will then be given by Figure 2.

In the estimation of K_N the choice of an appropriate level of the risk of exceedence (P_N) is a matter requiring careful consideration particularly in relation to partial factors which are almost always subsequently applied to loading values in design procedures. A discussion of this important aspect is given in Section B1 of Appendix B.

6. TERRAIN PARAMETERS z_0 and d

6.1 Surface Roughness Parameter z_0

The surface roughness parameter, z_0 , is a measure of the retarding effect that the surface in question has on the wind speed near the ground. It is a parameter in the mathematical model of the atmospheric boundary layer (described in Appendix A) used to derive the factors used in Equations (3.1) and (3.3). Typical values (derived by the method discussed in Section A1.3 of Appendix A) are listed in Table 13.1. The values given are average values applicable to upwind fetches of comparatively uniform roughness where the general description of the terrain fits a particular terrain category in Table 13.1.

In the special case of marine roughness, there is an interaction between the wind and waves. In general, as wind speed increases so does wave height* and hence surface roughness also increases. Using the Charnock relationship to fit the trend of experimental data (as described in Section A1.3 of Appendix A) the simple relationship, for $V_{10} > 10$ m/s,

$$z_0 = \frac{u_{*r}^2}{70g} \quad (6.1)$$

is obtained where g is the acceleration due to gravity and u_{*r} is a reference friction velocity corresponding to $z_{0r} = 0.01$ m. Thus, from Equation (A1.11), $u_{*r} = 0.0579 V_{10,r}$ and u_* (corresponding to z_0) is equal to $u_{*r} K_{s*}$.

6.2 Effective Height for Rough Terrain; Zero-plane Displacement d

The application of Equation (3.1) or (3.3) to rough terrain, *e.g.* built-up areas or forests, has important limitations. The flow between obstructions near ground level is very complex and no prediction of wind speed can be made with any certainty. The equations apply only to heights above the general level of the surrounding obstructions and it is necessary to define a displacement plane (called the zero-plane displacement) to which all heights are referred (see Sketch 6.1). The height, d , of this zero plane above the ground is generally less than the general height, H , of surrounding buildings. In practice it will depend on the plan-area density of surface roughness elements, λ . Data obtained from various wind-tunnel investigations^{7, 9, 15} were used to derive a correlation between $(H - d)/z_0$ and λ . This correlation (for $\lambda < 0.8$) is given by Figure 3 and is represented by

$$\frac{H - d}{z_0} = 4.3(1 - \lambda) + 10 \exp(-90\lambda^{1.5}) \quad (6.2)$$

$$\text{so that} \quad d = H - z_0[4.3(1 - \lambda) + 10 \exp(-90\lambda^{1.5})] \quad (6.3)$$

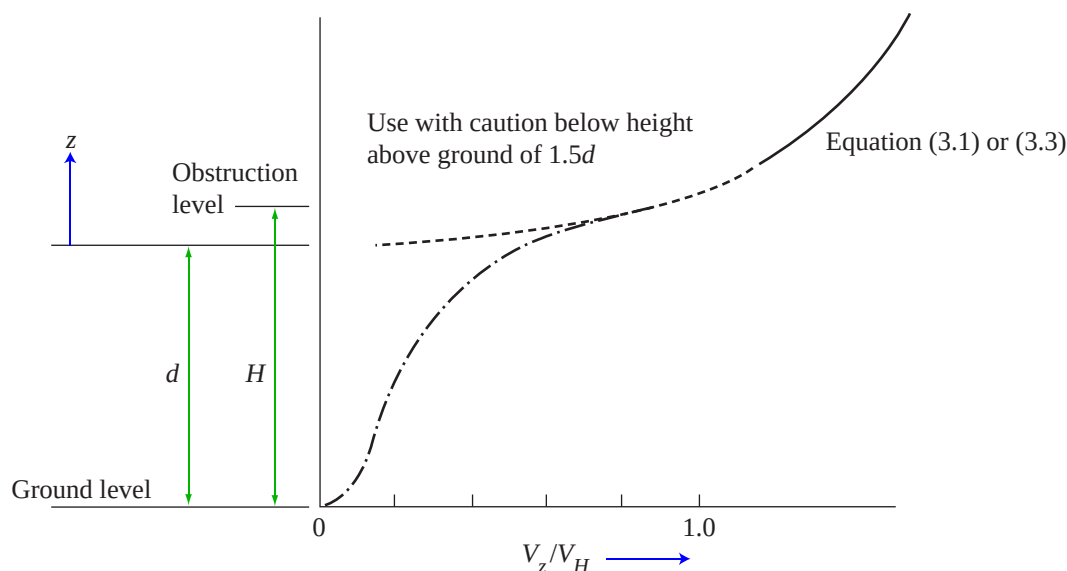
which for $\lambda \geq 0.2$ reduces to

$$d = H - 4.3z_0(1 - \lambda). \quad (6.4)$$

Equation (6.2) was derived from data for building-block type roughness but data from other sources^{8, 10} suggest that it is also applicable to vegetation-type roughness such as forests and crops.

* Wave height is not only dependent on local wind speed but is affected by disturbances propagated to the site from a wide area.

Typically, in a city such that $H \approx 25$ m and $z_0 \approx 0.8$ m, $H - d \approx 2.5z_0$ since λ is approximately 0.4 in a city centre. In general, for other than built-up areas or wooded terrain, it can be assumed that $d = 0$.



Sketch 6.1 Variation of mean wind speed with height near the ground for certain rough surfaces (see text)

Below a height above the ground of about $1.5d$ the relationship given by Equations (3.1) or (3.3) cannot be used with any certainty. As a general guide for obstacles with homogeneous porosity (*e.g.* forests and tall crops) the mean wind profile below general obstruction height takes the form illustrated in Sketch 6.1. In general for town and city centres, the assumption of homogeneity breaks down and details of the porosity (gaps between buildings) predominate. In this case the wind speed at heights below the general obstruction level may be at least equal to, and in some circumstances greater than, the wind speed at the general obstruction level.

7. SURFACE ROUGHNESS FACTORS K_{s*} AND K_s

The factors K_{s*} and K_s in Equations (3.1) and (3.3) respectively allow for the difference between the local terrain roughness (z_0) at the site and the terrain roughness for which the reference wind speed is applicable.

The factor K_{s*} in Equation (3.1) is defined as

$$K_{s*} = u_{*}/u_{*r} \quad (7.1)$$

where u_{*} and u_{*r} are the friction velocities appropriate to z_0 (for the site) and z_{0r} . The sites are assumed to be sufficiently close for the gradient wind speed to be the same in both cases. The values of K_{s*} given in Figure 4 have been derived as explained in Section A1.3 of Appendix A and are closely represented (to within about 3%) by

$$K_{s*} = \frac{\ln(10^5/z_{0r})}{\ln(10^5/z_0)} \quad (7.2)$$

The derivation of K_{s*} assumes that an equilibrium boundary layer applies for both the reference terrain and the site terrain; when this is not so at the site in question because of changes in z_0 upwind of the point in question the factor K_x (see Section 9) in Equation (3.5) will be different from unity.

The factor K_s in Equation (3.3) is defined as

$$K_s = V_{10}/V_{10,r} \quad (7.3)$$

where V_{10} and $V_{10,r}$ are the mean wind speeds at $z = 10$ m over uniform terrains z_0 and z_{0r} corresponding to the site in question and a nearby reference terrain. The values of K_s given by Figure 5 have been derived as explained in Section A1.3 of Appendix A and are closely represented (to within about 2%) by the simplified equation

$$K_s = \frac{\ln(10^5/z_{0r})}{\ln(10^5/z_0)} \frac{\ln(10/z_0)}{\ln(10/z_{0r})}. \quad (7.4)$$

As with K_{s*} the derivation assumes that an equilibrium boundary layer applies for both terrains; when this is not so at the site in question because of changes in z_0 upwind of the point in question, values for the factor K_x (Section 9) in Equation (3.5) will be different from unity. However, in this situation it is more convenient to use Equation (3.1) with K_{s*} since values of u_* are required to estimate K_x .

8. VARIATION OF MEAN SPEED WITH HEIGHT (Equilibrium Boundary Layer)

When the fetch (x) of uniform terrain upwind of the site in question is sufficiently long (larger than about 100 km) the boundary layer can be considered to be in equilibrium, *i.e.* the variation of wind speed with height does not change with increasing x and the factor K_x in Equation (3.5) is unity. In this situation the variation of the hourly-mean wind speed with height is given either by the factor $K_{z*} = V_z/u_*$ or the factor $K_z = V_z/V_{10}$ in Equations (3.1) and (3.3) respectively where V_z , V_{10} and u_* all relate to values at the same site.

The factors K_{z*} and K_z , given by Equations (A1.8) and (A1.10) in Appendix A and plotted in Figures 6 and 7, are dependent primarily on z and z_0 but are also (more weakly) dependent on the values of f/u_* and f/V_{10} respectively. The main charts in Figures 6 and 7 are presented for a value of $f/u_* = 6 \times 10^{-5}$ rad/m and a value of $f/V_{10} = 4 \times 10^{-6}$ rad/m which are typical of middle latitudes ($f \approx 10^{-4}$ rad/s) and extreme wind speeds with a 50-year return period; the inset chart on each Figure gives a correction factor which allows for the effect on K_{z*} and K_z of other values of f/u_* and f/V_{10} .

In practice, the effect of upwind changes in terrain roughness will usually have to be taken into account and the method of allowing for this requires a knowledge of u_* . Thus, in this situation, it is usually more convenient to use Equation (3.1) with K_{z*} than Equation (3.3) with K_z .