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Strong winds in the atmospheric boundary layer
Part 2: discrete gust speeds

Associated software: VIEWpac E0108 (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 prevously 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 2: discrete gust speeds

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1. NOTATION AND UNITS

		SI Unit
d	displacement height of zero-plane above ground (see Figure 3 of ESDU 82026[4])	m
F	value of fetch x of uniform terrain upwind of site necessary for equilibrium boundary layer to exist at site $(F \approx 50\ \text{km})$	m
f	Coriolis parameter, $f = \Omega \sin\phi$ (see Section A1 of ESDU 82026)	rad/s
g	peak factor, $(K_\tau - 1)/I_u$	
h	gradient height or equilibrium boundary layer height above which V_z and $\hat{V}_z$ are independent of the underlying terrain	m
$\hat{h}_i$	height of internal layer at fetch x (see Sketch 4.1)	m
I_u	intensity of turbulence for equilibrium conditions; σ_u/V_z at height z	
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 of ESDU 82026[4])	
K_{s*}	terrain roughness factor used in relating mean wind speeds at nearby sites with different terrains; given by u_*/u_{*r} (see Section 7 of ESDU 82026[4])	
K_τ	gust factor for equilibrium conditions; $\hat{V}_z/V_z$	
K_x	fetch factor accounting for effect on mean-hourly wind speed of upwind change in terrain roughness; V_{zx}/V_z	
$\hat{K}_x$	fetch factor accounting for effect on gust of upwind change in terrain roughness; $\hat{V}_{zx}/\hat{V}_z$	
K_{z*}	height factor accounting for effect of z on V_z; given by V_z/u_* (see Section 8 of ESDU 82026[4])	
${}^xL_u$	integral length scale of u-component of turbulence in mean wind direction	m
N	exposure period or anticipated structure life	years
n	exponent in definition of R	
P_1	probability of an extreme wind speed being equalled or exceeded in any one year; $P_1 = 1/T$	
P_N	probability of an extreme wind speed being equalled or exceeded at least once in N years	

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P_{Nr}	probability of equalling or exceeding the reference wind speed of return period T_r in N years	
R	roughness-change parameter for first roughness change upwind of site; $R = \lvert \ln(z_0/z_{01}) \rvert / [u_*/(fz_0)]^n$ where $n = 0.23$ and 0.14 for smooth-to-rougher terrain and rough-to-smoother terrain respectively	
R_{j-1}	roughness change parameter for jth roughness change upwind of site; $R_{j-1} = \lvert \ln[z_{0j}/z_{0,j-1}] \rvert / \{[u_*/(fz_0)]^n\}_{j-1}$	
T	return period; average period between consecutive occurrences of particular extreme value	years
T_o	time interval within which wind speed applies or observation period over which wind speed is measured (see Sketch 3.1)	s
T_u	integral time scale of u-component of turbulence, ${}^xL_u/V_z$	s
t	time	s
u_*	friction (or surface shear) velocity at site in question	m/s
$u(t)$	fluctuating component of wind speed in mean wind direction	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 50 km (*i.e.* equilibrium boundary-layer conditions)	m/s
V_h	gradient wind speed, V_z at $z = h$	m/s
$\hat{V}_z$	expected (or mean) maximum gust speed at height z averaged over τ seconds, occurring in period of 1 hour assuming equilibrium boundary-layer conditions ($x > 50$ km)	m/s
$\hat{V}_{zx}$	expected (or mean) maximum gust speed at height z averaged over τ seconds, occurring in period of 1 hour at site a distance x downwind of change in terrain roughness	m/s
x	distance (fetch) that uniform terrain roughness extends upwind of site in question (see Sketch 4.1)	m
x_1	length of uniform terrain between first and second step changes in terrain roughness upwind of site in question (see Sketch 1.1)	m
z	height measured from zero-plane displacement	m
z_0	surface roughness parameter at site (see Table 13.1 of ESDU 82026)	m
ν	zero crossing rate of $u(t)$, see Appendix A	l/s
σ_u	standard deviation of $u(t)$ for $\tau \to 0$ and $T_o = 3600$ s (see Sketch 3.1)	m/s
τ	gust duration or averaging time	s
ϕ	local angle of latitude	degree
Ω	angular rate of rotation of Earth; 72.9×10^{-6} rad/s	rad/s

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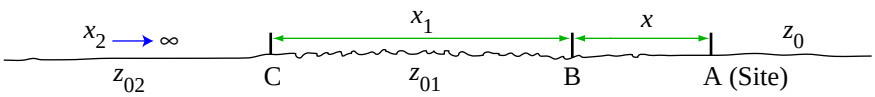
Subscripts

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



Sketch 1.1

r	relates to reference, or standard, conditions
x	denotes values at site with step change in terrain roughness a distance x upwind and indicates non-equilibrium boundary-layer conditions
z	relates to value at height z

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2. PURPOSE, SCOPE AND APPLICABILITY

2.1 Purpose and Scope

In ESDU 82026[4] data are provided for estimating the variation of the design hourly-mean wind speed (*i.e.* that averaged over 1 hour) with height above the ground, with terrain roughness at the site and upwind of the site, and with probability of occurrence. The purpose of this Item is to give further data from which the expected maximum wind speed averaged over much shorter periods may be estimated from a knowledge of the hourly-mean value. A definition of the expected maximum τ-second wind speed (commonly known as a gust) is given in Section 3.1.

These data are applicable in the estimation of the overall wind loading due to the action of a discrete gust on simple structures. The applicability and limitations of the discrete-gust approach are outlined in Section 2.2.

The estimation of gust speeds in this Item is based on a gust factor method which relates a maximum gust speed averaged over τ seconds to the corresponding hourly-mean wind speed given by ESDU 82026. This method also takes into account non-equilibrium boundary-layer effects produced by upwind fetches of terrain that have a different surface roughness from that at the site in question. In relation to gust factors, this effect manifests itself through changes in the turbulence characteristics of the fluctuating wind. The method which is described in Appendix A, takes into account the following main parameters.

(i) The averaging time, τ, of the maximum gust speed.

(ii) The observation or time interval, T_o, in which the maximum gust speed occurs.

(iii) The height of the point in question above the ground.

(iv) The surface roughness of the local terrain at the site.

(v) Changes in terrain roughness upwind of the site.

(vi) The probability of the maximum gust speed being exceeded.

The calculation procedures given in this Data Item (see Section 5) have been simplified for hand-calculation purposes; the full methods have been incorporated subsequently into a software package (see Section 2.3).

2.2 Applicability

The information presented is for strong winds ($V_{10} > 10$ m/s) associated with fully-developed weather systems in temperate latitudes in which the assumption of a neutrally-stable atmosphere is valid. The data apply for heights between ground level and the edge of the Earth's boundary layer which is between about 500 m and 3000 m deep depending on wind speed and surface roughness.

The use of maximum gust data to estimate wind loading is often referred to as the 'discrete-gust loading approach' as compared with the 'time- approach' which uses the hourly-mean speed and the statistical properties of turbulence to predict maximum wind loads. The discrete-gust method is applicable to structures which are

(i) sufficiently small that a discrete gust averaged over τ seconds completely envelops the structure or any component part of the structure under consideration,

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(ii) sufficiently stiff for wind effects to be determined by static methods.

Limitations on size and stiffness are given in Reference 3.

The significance of the first 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).

Where the discrete-gust approach is inapplicable the 'time-' approach can be applied. This uses the hourly-mean wind speed to calculate a mean wind loading onto which is superimposed a component to account for fluctuations in wind speed about the hourly mean. This approach is discussed in ESDU 82026[4].

2.3 Use of the Data Item; Related Computer Program

The maximum gust speed averaged over τ seconds occurring in a period of 1 hour is related to the corresponding hourly-mean wind speed for the same period. The starting point of a gust speed calculation is therefore to establish the corresponding hourly-mean wind speed for the given design conditions (exposure period, risk of exceedance, *etc*.) and this requires the data given in ESDU 82026. The calculation sheets given in this Item as Tables 8.1, 8.2 and 8.3 include, for convenience, the estimation of the hourly-mean values and they provide a complete summary of the calculation procedure for estimating maximum gust speeds.

The calculation sheets are self-explanatory but the user is recommended to read the background notes in the following Sections and to follow the example given in Section 6.

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 01008[2]) which calculates both mean wind speeds and gusts for multiple roughness changes over flat or hilly terrain. This package is in the form of a Visual Basic module running in Microsoft Excel. It is recommended that the software is used where more than one roughness change and/or topographic effects are to be accounted for.

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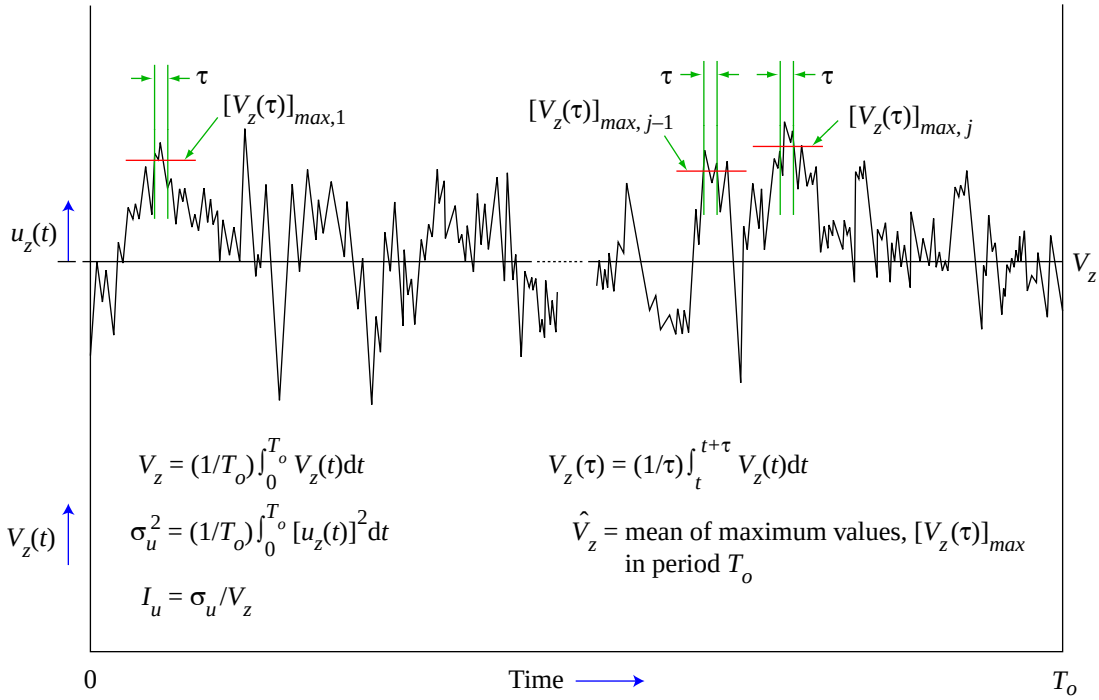
3. BACKGROUND INFORMATION AND DEFINITIONS

The mechanisms that produce and influence the nature of the wind near the surface of the Earth are described in Appendix A of ESDU 82026. The slowing down of the wind near the surface of the Earth is caused by horizontal drag forces induced by ground obstacles. These shearing forces are transmitted upwards through an exchange of momentum between successive layers of the atmosphere; they are a maximum at the surface and decrease to zero at the gradient height, *h*. The process of momentum exchange is the mechanism leading to the generation of fluctuations in the flow which is termed turbulence.

3.1 Mean Wind Speed, Turbulence Intensity, Maximum Gust Speed

The instantaneous wind speed, $V(t)$, varies with time as illustrated in Sketch 3.1. The mean wind speed, V_z, is the average of $V(t)$ at height z over a relatively long time period, T_o, usually 1 hour. At any time, t, the



Sketch 3.1 Definition of wind speed characteristics

instantaneous wind speed is given by

$$V_z(t) = V_z + u_z(t) \tag{3.1}$$

where $u_z(t)$ is the component in the direction of the mean wind of the fluctuations due to turbulence. The mean value of $u_z(t)$ over the period T_o is zero but an overall measure of the degree of turbulence is given by the mean square or variance

$$\sigma_u^2 = \frac{1}{T_o}\int_0^{T_o} [u_z(t)]^2 \mathrm{d}t. \tag{3.2}$$

The quantity σ_u/V_z is called the *intensity of turbulence* and is denoted by I_u.

The instantaneous wind speed can be averaged over much shorter periods than 1 hour. For example, from the wind speed record illustrated in Sketch 3.1 it is possible to obtain a continuous of values of τ-second gust speeds, $V_{z\tau}$, averaged over a period τ (this could either be a few seconds or a few minutes); $\hat{V}_z$ is

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then the expected maximum* of these values occurring in the period T_o. In practice, standard anemometers have finite response time so that the 'instantaneous' values in the wind speed record are actually gust speeds averaged over a few seconds. For typical standard cup anemometers and their recording equipment this minimum averaging time (τ) varies with wind speed and, as shown by Greenway[10], is approximately 2.8 D_{am}/V_z seconds where D_{am} is the distance constant of the instrument. Typically, $D_{am} \approx 7$ metres for wind speeds above about 5 m/s so that τ varies from about 4 s for low wind speeds down to about 1 s or less for extreme winds; this lower value will be limited by the response time of the recording system.

The ratio $\hat{V}_z/V_z$, of the expected maximum τ-second gust to the mean wind speed for the period T_o (usually 1 hour) within which $\hat{V}_z$ occurs, is called the *gust factor*, K_τ. This factor is primarily dependent on the degree of turbulence present in the wind (measured by I_u) and the averaging period, τ. The factor $(K_\tau - 1)/I_u$ is often called the *peak factor*, *g*.

It is important to note that, whilst $\hat{V}_z$ will increase in value with increasing height, the maximum values will not occur simultaneously at all levels because of the way that turbulence is propagated through the boundary layer. On a tall structure this effect acts to alleviate the gust loading that would result if all maximum gusts occurred at the same time. However, although it is perhaps misleading to describe the variation of $\hat{V}_z$ with height as a time-independent function, the locus of such values will be described in this Item as the profile of $\hat{V}_z$ and equations are given to determine this profile.

* Further information on the statistical significance of expected maxima is given in Section A1.2 of the Appendix.

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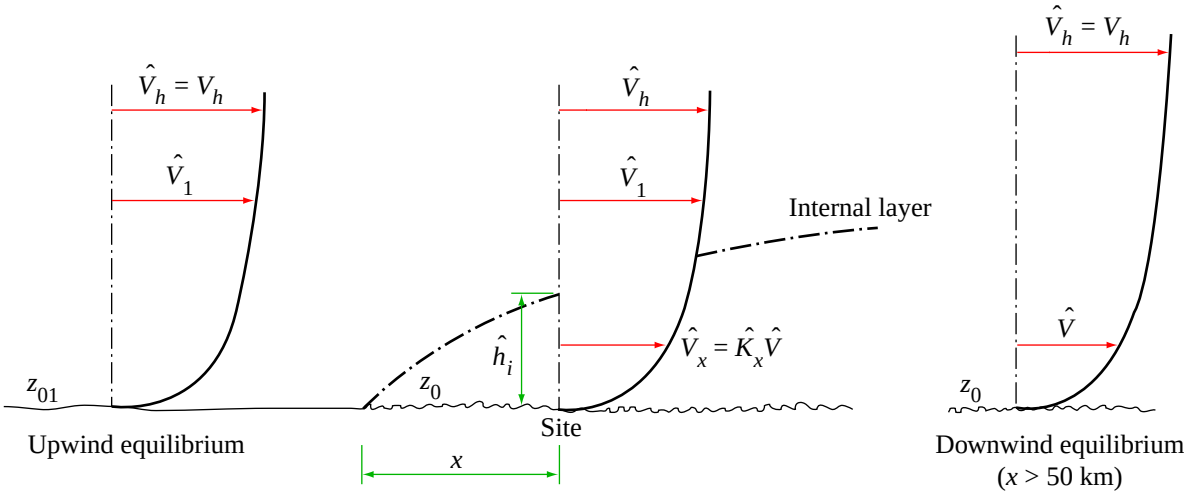
4. THE FACTORS AFFECTING GUST SPEED AND THEIR CALCULATION



Sketch 4.1 Illustration of gust profiles upwind and downwind of a sudden change in terrain roughness

The mechanisms that produce and influence the nature of the wind near the surface of the Earth are described in ESDU 82026. In summary, within the atmospheric boundary layer, the wind speed progressively increases with increasing height above the ground up to a height called the gradient height, h, as illustrated in Sketch 4.1. For strong winds the depth of this boundary layer can vary between about 500 m and 3000 m depending on the roughness of the underlying terrain and strength of the wind. At the gradient height the wind speed is independent of the underlying terrain.

Providing the wind has blown over a fetch of about 50 to 100 km of uniform terrain the boundary layer is in eqilibrium with the underlying terrain and the variation of mean wind speed or gust speed with height does not depend on the fetch, x, of upwind uniform terrain.

In practice it is exceptional that a sufficiently long upwind fetch of uniform terrain occurs for an equilibrium boundary layer to exist. The open sea, large plains and extensive forests which extend more than about 50 km are examples where an equilibrium boundary layer can exist; in countries like the United Kingdom, apart from stretches of fairly flat open country away from the coastal regions, this situation is rare. There may be several changes in the upwind terrain roughness within a few kilometres of the site in question; the variation of wind speed with height is then no longer independent of the fetch, x.

Immediately downwind of a change in terrain roughness, such as at the edge of a town or at the coast, a new internal layer begins to grow as illustrated in Sketch 4.1. Within the new layer the flow is not in equilibrium and the wind or gust profile and its turbulence characteristics depend on the location of the site with respect to the roughness change. Above this new layer it can be assumed that for all practical purposes the wind profile is the same as that immediately upwind of the roughness change, at the same level, as illustrated in Sketch 4.1.

4.1 Overall Summary

In the general case, given a hourly-mean wind speed, it will be required to estimate the corresponding expected maximum τ-second gust speed. The expected maximum value of τ- second gust occurring in

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