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Strong winds in the atmospheric boundary layer

Part 2: discrete gust speeds

Associated software: VIEWpac E0108 (Item No. 01008)

ESDU DATA ITEMS

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We are constantly striving to develop new work and review data already issued. Any comments arising out of your use of our data, or any suggestions for new topics or information that might lead to improvements, will help us to provide a better service.

THE PREPARATION OF THIS DATA ITEM

The work on this particular Data Item which supersedes Item No. 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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Prof. Dr-Ing H.J. Niemann*	–	Ruhr-Universität, Bochum, Germany
Dr A.G. Robins	–	University of Surrey
Mr G. Wiskin	–	Crown Castle UK Ltd

* Corresponding Member

The construction and subsequent development of the Data Item was undertaken by

Mr N. Thompson — Consultant to ESDU

STRONG WINDS IN THE ATMOSPHERIC BOUNDARY LAYER. PART 2: DISCRETE GUST SPEEDS

CONTENTS

STRONG WINDS IN THE ATMOSPHERIC BOUNDARY LAYER. Part 2: Discrete Gust Speeds

1. NOTATION AND UNITS

		SI Unit
d	displacement height of zero-plane above ground (see Figure 3 of Item No. 82026[4])	m
F	value of fetch x of uniform terrain upwind of site necessary for equilibrium boundary layer to exist at site ($F \approx 50$ km)	m
f	Coriolis parameter, $f = \Omega \sin\phi$ (see Section A1 of Item No. 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 Item No. 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 Item No. 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 Item No. 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; $R = \left\|\ln(z_0/z_{01})\right\|/[u_*/(fz_0)]^n$ 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; $R_{j-1} = \left\|\ln[z_{0j}/z_{0,j-1}]\right\|/\{[u_*/(fz_0)]^n\}_{j-1}$	
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 Item No. 82026)	m
ν	zero crossing rate of $u(t)$, see Appendix A	1/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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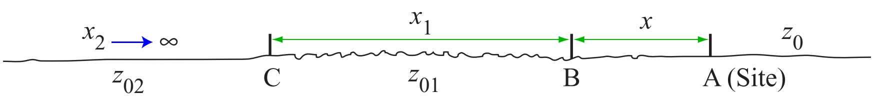
Subscripts

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

2. PURPOSE, SCOPE AND APPLICABILITY

2.1 Purpose and Scope

In Item No. 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 Item No. 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-series 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,

(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-series' 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 Item No. 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 Item No. 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.

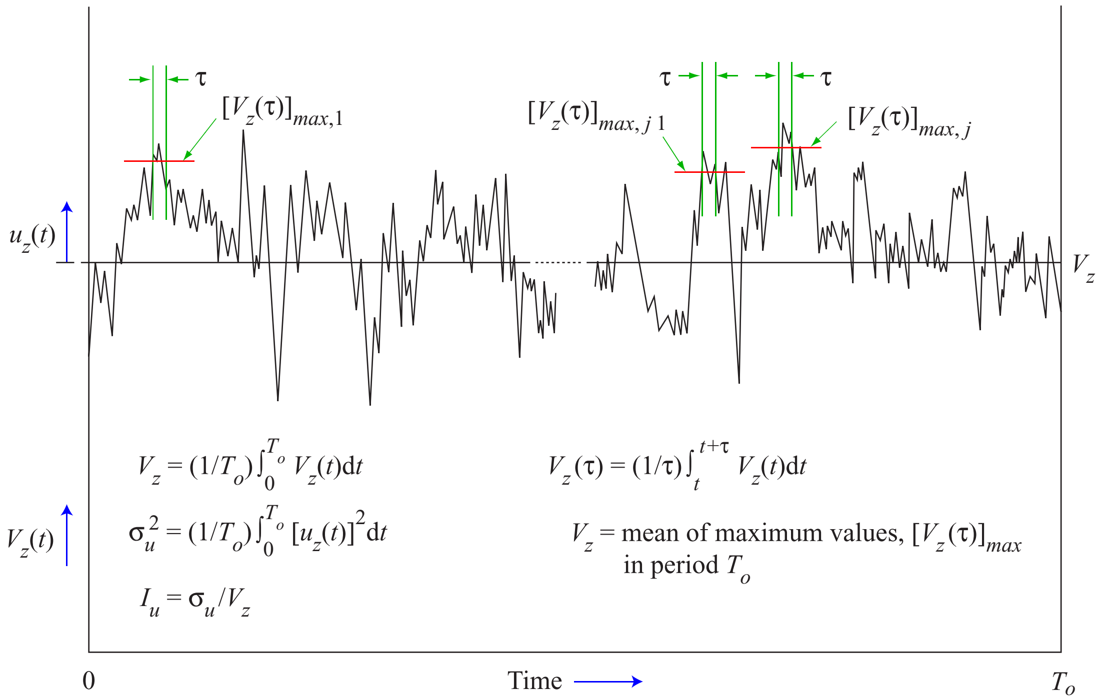
The simplified procedures given in this Data Item accounting for terrain with roughness changes have been derived (as described in Appendix A) for use in hand calculations. The full methods have been incorporated into a computer program VIEWpac E0108, (described in ESDU 01008[2]) which calculates both 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.

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 Item No. 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, $\bar{V}_z$, 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

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

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 $\sigma_u/\bar{V}_z$ 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 series 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);

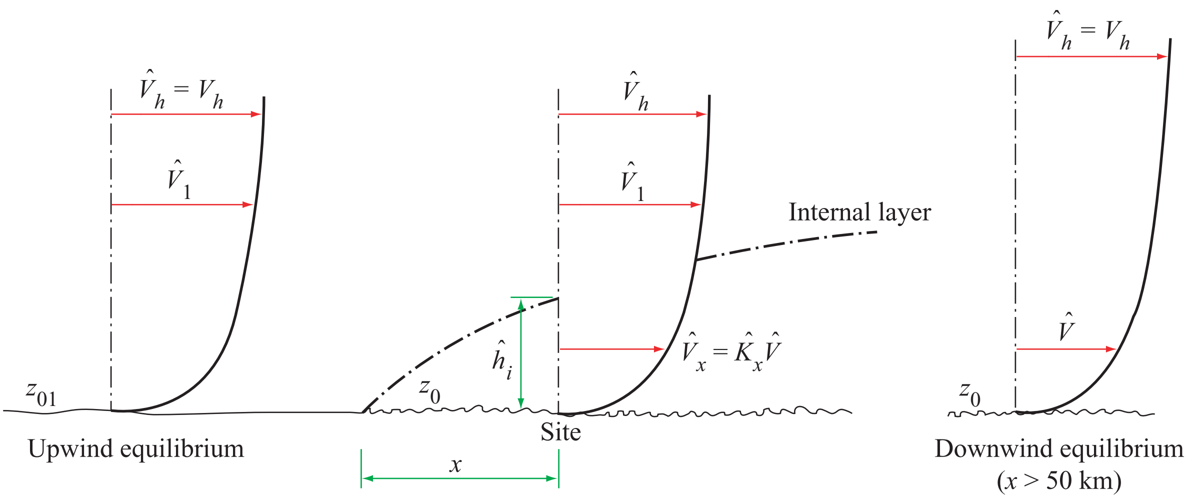
$\hat{V}_z$ is then the expected maximum* of these values occurring in the period T_o. In practice, standard anemometers have finite response time so that the 'instantaneous' values in the wind speed record are actually gust speeds averaged over a few seconds. For typical standard cup anemometers and 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.

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 Item No. 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 any one hour within the internal layer at the site illustrated in Sketch 4.1 is given by

$$\hat{V}_{zx} = \hat{V}_z \hat{K}_x = V_z K_\tau \hat{K}_x \qquad (4.1)$$

and V_z is the corresponding hourly-mean wind speed (see Section 4.2) with the same probability of exceedance as the gust and is calculated using Item No. 82026 assuming that equilibrium conditions exist at the site (i.e. $x > 50$ km). The factor K_τ (see Section 4.3) expresses the relationship between $\hat{V}_z$ and V_z again assuming equilibrium conditions exist at the site, and the fetch factor $\hat{K}_x$ (see Section 4.4) accounts for the influence of surface roughness changes upwind of the site on the gust speed.

The calculation of the gust profile for the special case where equilibrium conditions can be assumed to exist at the site is covered in Section 5.1 and by the calculation sheet in Table 8.1. The calculation procedure for the more general situation where there is a single change in terrain roughness upwind of the site is described in Section 5.2 and summarised in the calculation sheet in Table 8.2. However, for more than one roughness change it is recommended that the software referred to in Section 2.3 is used.

A comparison of measured gust factors with predicted values for eleven sites from various sources[5,6,8,9,13] and wind-tunnel data[10], indicates that the overall uncertainty of the method described in this Item is about $\pm 6\%$ when the effects of any upwind changes in roughness are taken into account. The data examined were for a variety of sites ranging from a large lake to the centres of large towns.

4.2 Hourly-mean Wind Speed, V_z

As part of the calculation it is necessary to estimate the hourly-mean wind speed at the site assuming that equilibrium conditions exist there (*i.e.* that $x > 50$ km). This is obtained using Item No. 82026 which takes into account the following factors.

(i) Geographic location.

(ii) Height above the ground (z).

(iii) Surface roughness at the site described by the parameter z_0 (see Table 13.1 in Item No. 82026).

(iv) The exposure period of the structure under consideration and the probability of exceeding the wind speed within this period.

Item No. 82026 also provides information on the directional occurrence of extreme winds in the UK.

The calculation sheets in Tables 8.1, 8.2 and 8.3 include the estimation of hourly-mean wind speeds but data from Item No. 82026 are required for this.

4.3 The Gust Factor, K_τ for Uniform Terrain (Equilibrium Conditions)

The factor K_τ relates the hourly-mean wind speed to the corresponding maximum τ-second gust at a site assuming equilibrium conditions exist there (*i.e.* $x > 50$ km). It is defined as

$$K_\tau = \hat{V}_z / V_z = 1 + g I_u \qquad (4.2)$$

and is primarily dependent on the averaging, or duration, time of the gust and the intensity of turbulence, I_u, at the site for equilibrium conditions. Values of I_u are dependent on the surface roughness parameter, z_0, and height, z, and are given by Figure 1. There is also a relatively small dependence of I_u on the gradient speed, V_h, as shown by the inset chart in Figure 1; for typical design wind speeds this correction will be small and can be ignored. The peak factor g is given by Figure 2. Section A1 in the Appendix explains the derivation of these data and provides general equations for all the relevant parameters.

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4.4 Effect of Changes in Terrain Roughness Upwind of the Site (Non-equilibrium Conditions); the Fetch Factor $\hat{K}_x$

A change in surface roughness causes changes in the profiles of hourly-mean wind speed and turbulence. Consequently, the gust speed also changes with distance downwind of the roughness change up to about 50 km downwind when equilibrium conditions are again established. Within the new internal layer the factor $\hat{K}_x$ accounts for the influence of a roughness change on the gust speed $\hat{V}_z$ that would occur at the site under equilibrium boundary layer conditions. It allows for the effect of the upwind roughness change on the mean flow (V_z) and also for the additional effect arising from changes to the local turbulence. Within the inner layer $\hat{K}_x$ is independent of height and is given by Figures 3 and 4. As $x \to \infty$, $\hat{K}_x \to 1.0$ and as $\tau \to 3600$ s, $\hat{K}_x \to K_x$ and $K_\tau \to 1.0$. The derivation of these data is explained in Section A2 of the Appendix which also provides equations for these factors.

5. CALCULATION PROCEDURE

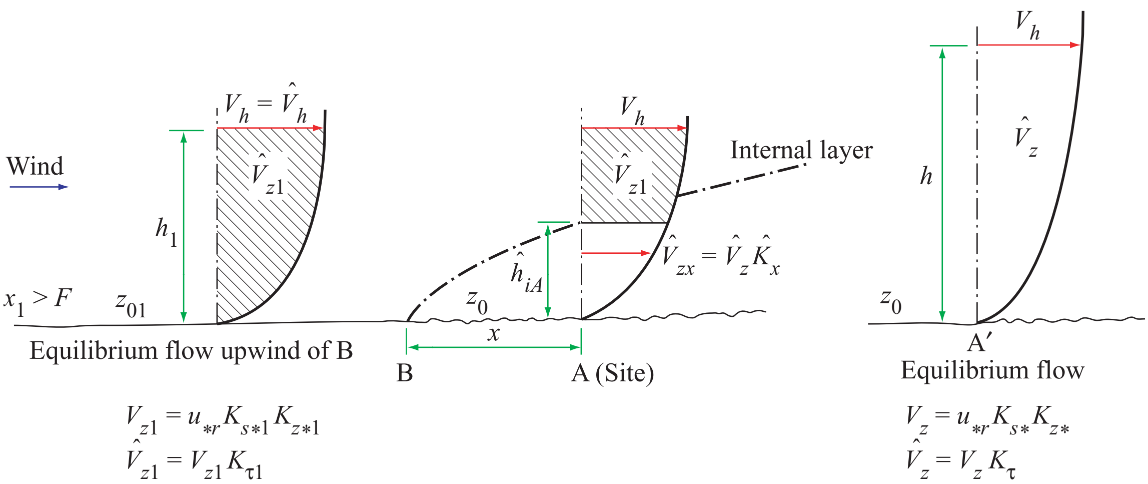
The following procedures are suitable for hand calculation but where more than one terrain roughness change applies it is recommended that the software package referred to in Section 2.3 is used.

5.1 Uniform Terrain; Equilibrium Conditions at the Site

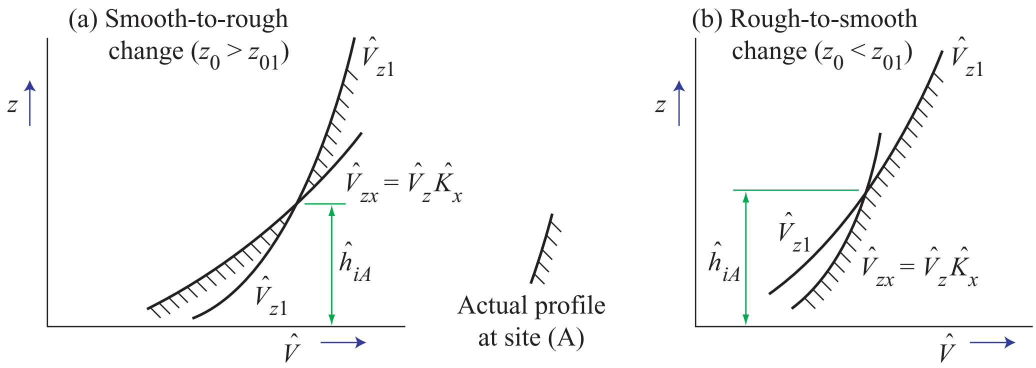
When the terrain upwind of the site can be considered to be uniform for about 50 km then it may be assumed that equilibrium conditions exist at the site. In this case the calculation of the gust speed, $\hat{V}_z$, from the hourly-mean wind speed, V_z, involves only the estimation of I_u (Figure 1) and hence K_τ (Figure 2). The procedure for this situation is summarised in Calculation Sheet 1 in Table 8.1 which also includes the estimation of the hourly-mean wind speed using Item No. 82026.

5.2 Single Step Change in Terrain Roughness

The procedure in the calculation sheet in Table 8.2 applies for either a smooth-to-rough or a rough-to-smooth change and assumes that the boundary-layer wind profile can be considered to be in equilibrium just upwind of the step change at B in Sketch 5.1 (*i.e.* the wind speed profile $\hat{V}_x$ is not changing as x_1 increases). The procedure calculates the gust profile at a location A sited a distance x downwind of the step change in roughness. It forms the basis for a more general procedure (described in Section 5.3) for estimating the effect of more than one step change in terrain roughness on the wind speed profile. It is recommended that Calculation Sheet 2 in Table 8.2 is used since all the relevant factors are then automatically included; the following description serves only to explain in more detail the various steps in the calculation sheet.



Sketch 5.1 Illustration of wind profiles at the site, and upwind and far downwind of the change in roughness



Sketch 5.2 Illustration of calculation procedure

In the first stage, using Item No. 82026, it is necessary to calculate the upwind and downwind hourly-mean wind speed profile V_{z1} and V_z (over the required height range) corresponding to the surface roughnesses z_{01} and z_0, assuming eqilibrium conditions.

In the second stage the gust factor, K_τ, and the gust fetch factor $\hat{K}_x$ are determined so that the locus of values $V_z K_\tau \hat{K}_x$ can be calculated over a range of z. The maximum gust profile, $\hat{V}_{z1}$ (corresponding to upwind equilibrium conditions) is calculated from $V_{z1}K_{\tau 1}$. The resulting maximum gust profile at the site ($\hat{V}_{zx}$) is then found by superimposing the two profiles ($V_z K_\tau \hat{K}_x$ and $V_{z1}K_{\tau 1}$) which will intersect at a height $z = \hat{h}_{iA}$; reference to Sketch 5.1 then shows that for $z < \hat{h}_{iA}$, $\hat{V}_{zx} = V_z K_\tau \hat{K}_x$ and for $z > \hat{h}_{iA}$, $\hat{V}_{zx} = V_{z1}K_{\tau 1}$.

Steps 1 to 14 calculate u_{*r} for the reference conditions (which might be, for example, the once in 50 year extreme hourly-mean wind speed at a height of 10 m above flat open terrain).

Steps 15 to 21 calculate (from u_{*r}) the friction velocities u_* and u_{*1} corresponding to downwind and upwind equilibrium conditions for z_0 and z_{01} respectively.

Steps 22 to 28, for the given values of x and gust duration τ, together with the known values of z_0, z_{01} and u_*, give the gust fetch factor $\hat{K}_x$.

Steps 29 to 34 determine the upwind and downwind hourly-mean wind speed profiles V_z and V_{z1} from u_* and u_{*1} respectively for the required height range.

Steps 35 to 38 calculate the appropriate turbulence intensity parameters I_u and I_{u1}, corresponding to the V_z and V_{z1} profiles, which in turn give the equilibrium gust factors K_τ and $K_{\tau 1}$.

Steps 39 to 43 give the values of $V_z K_\tau \hat{K}_x$ and $V_{z1}K_{\tau 1}$ for the appropriate range of z from which the height $\hat{h}_{iA}$ at which these two profiles intersect can be identified. The site value of the maximum τ-second gust variation with height is then given by

$$\hat{V}_{zx} = V_z K_\tau \hat{K}_x \quad \text{for} \quad z < \hat{h}_{iA} \qquad (5.1)$$

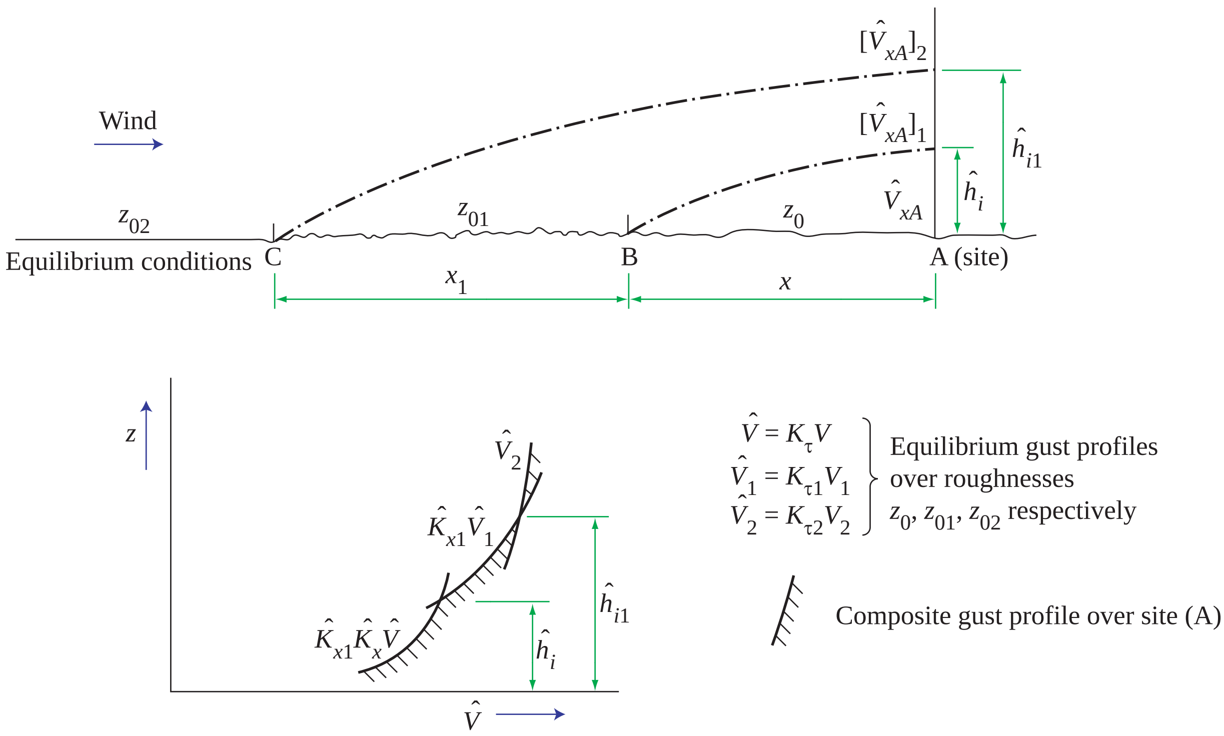
and

$$\hat{V}_{zx} = V_z K_{\tau 1} \quad \text{for} \quad z > \hat{h}_{iA} \qquad (5.2)$$

5.3 Two or More Step Changes in Terrain Roughness

In some cases several changes in roughness may occur upwind of, and close to, the site in question. For example, the wind in passing over a town will experience, firstly, a change from relatively smooth to relatively rough terrain and, a change back from rough to smooth terrain. Alternatively, roughness changes from rough-to-smooth and then smooth-to-rough would be associated with the wind passing over a city containing a large park, or open country surrounding a large lake or inland sea.

The effect of multiple changes such as these is to generate a new internal layer at each step change which in turn influences the downwind variation of gust speed with height and fetch. This influence can be determined to a close approximation by adapting the method in Section 5.2 for a single step change in roughness.



Sketch 5.3 Two step changes in terrain roughness

The procedure for two step changes in roughness (Calculation Sheet 3 in Table 8.3) is illustrated schematically in Sketch 5.3. It applies for two arbitrary step changes but in principle it may be extended to any number although normally no more than two or three changes would be considered. Note that if $z_0 = z_{02}$ (see Sketch 5.3) and $x > x_1$ then, within the uncertainty of the method, the effect of the intermediate roughness change (z_{01}) can be ignored for the reasons described in Section 5.3.

For the example shown in Sketch 5.3 with two step changes in roughness the gust profile in the height range $\hat{h}_{i1} < z < \hat{h}_i$ is calculated as that originating from the single roughness change at C assuming independence from the second roughness change at B. Thus,

$$[\hat{V}_{xA}]_2 = \hat{V}_2 = K_{\tau 2} V_2 \qquad \text{for} \qquad z > \hat{h}_{i1} \qquad (5.3)$$

and

$$[\hat{V}_{xA}]_1 = \hat{K}_{x1} \hat{V}_1 \qquad \text{for} \qquad \hat{h}_i < z < \hat{h}_{i1} \qquad (5.4)$$

where $\hat{V}_1$ is the gust profile that would exist in equilibrium conditions over a roughness z_{01} and $\hat{K}_{x1}$ is the value of K_x given by Figures 3 and 4 with the parameter R given by

$$R_1 = \frac{|\ln(z_{02}/z_{01})|}{[u_{*1}/(fz_{01})]^n} \tag{5.5}$$

and the effective value of x given by $x + x_1$. As before, the exponent n is 0.23 for smooth-to-rougher terrain and 0.14 for rough-to-smoother terrain.

In the lower inner-layer, $z < \hat{h}_i$, with the assumption of equilibrium conditions at B, the gust profile over the site (A) would be given by $\hat{K}_x \hat{V}$ and the gust speed at $z = \hat{h}_i$ would be $\hat{V}_1$ instead of the actual value $\hat{K}_{x1} \hat{V}_1$. Thus the 'corrected' gust profile in the range $z < \hat{h}_i$ is given by

$$[\hat{V}_{xA}] = \hat{K}_{x1} \hat{K}_x \hat{V} \tag{5.6}$$

where $\hat{V}$ is the equilibrium gust profile over a roughness z_0.

The depth, $\hat{h}_i$, of the lower inner-layer over the site (A) is determined by the height at which the gust profile $[\hat{V}_{xA}]$ (Equation (5.6)) intersects with the gust profile $[\hat{V}_{xA}]_1$ (Equation (5.4)) as illustrated in Sketch 5.3. Similarly, the depth $\hat{h}_{i1}$ of the upper inner-layer is given by the intersection of the gust profiles given by Equations (5.3) and (5.4).

The procedure can be generalised for more step changes in roughness but in this case it is recommended that the computer program, E0108, referred to in Section 2.3 is used.

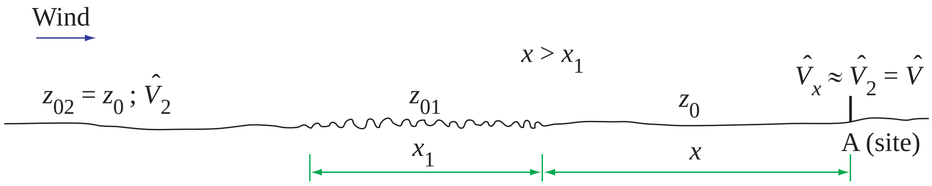
5.4 Simplifying Assumptions for Single and Multiple Roughness Changes

In many circumstances the following simplifying assumptions help to eliminate the need to consider more than a single step change in the upwind terrain roughness and in some cases the need to calculate the effects of any step change can be avoided altogether.

(i) In practice the change in terrain roughness may be gradual and not in the form of a step change. For the purposes of the calculation, a step change at an intermediate point can be assumed with constant (but different) values of z_0 on either side.

(ii) Unless the ratio of the larger value of z_0 to the smaller value in a single step change is greater than about 3, an average value of z_0 may be assumed to apply with no step change.

(iii) Results of using the method for two step changes in z_0 indicate that when z_0 at the site and upwind of the initial change are the same (*i.e.* $z_0 = z_{02}$) then, providing $x > x_1$, the gust profile over the site will have been approximately restored to its original upwind equilibrium condition over roughness z_{02}. This situation is illustrated in Sketch 5.4.



Sketch 5.4 Uniform terrain (z_0) with an intermediate region of different roughness (z_{01})

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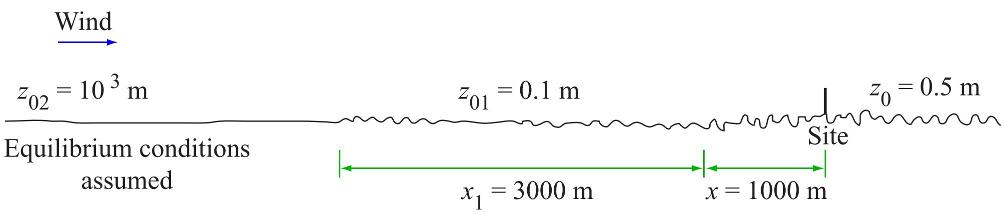
The implication of this is that the existence of, say, an intermediate upwind region (x_1) of trees in otherwise open country, or a park in a large city, can be ignored providing the site in question is located in the region $x > x_1$.

6. EXAMPLE

The gust loadings on a number of dish aerials mounted at various levels on a lattice tower, situated near the centre of a large town near the coast, are to be estimated. It is required to calculate the design expected maximum 3-second gust speed at levels between 40 m and 150 m above the ground corresponding to the hourly-mean wind speed which has a risk of $P_N = 0.05$ of being equalled or exceeded once in an exposure period of 50 years. From a map of extreme wind speeds it is assessed that the appropriate reference hourly-mean wind speed ($z_r = 10$ m, $z_{0r} = 0.01$ m) for the most adverse wind direction, is 22 m/s which represents the extreme wind for a return period of 50 years. Upwind of the site there are assessed to be several changes in terrain roughness, associated with a suburban area 1 km upwind of the site (stretching to the coast) and the sea beyond, as illustrated in Sketch 6.1. The zero-plane displacement height due to buildings surrounding the tower is assessed to be 20 m and the local angle of latitude of the site is 52°.

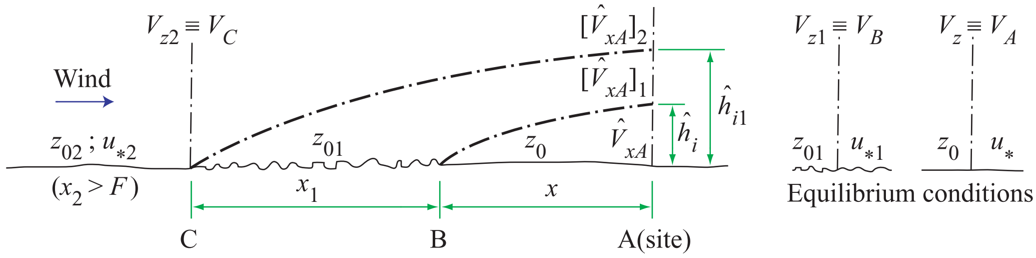


Sketch 6.1

The calculation of the profile of the maximum 3-second gust up to a height of 200 m above the zero plane (20 m above local ground level) is summarised on a copy of Calculation Sheet 3 – in Table 6.1.

The calculations have been taken to a greater height than required but the results indicate two transition zones, the first near $z = 60$ m, where the inner layers originating from the town centre ($z_0 = 0.5$ m) and the suburban area ($z_{01} = 0.1$ m) interact, and the second where the inner layer associated with the suburban area meets the marine boundary layer. The effect of non-equilibrium conditions at the site is most noticeable below about $z = 60$ m where the gust velocities are about 13% higher than would be obtained if equilibrium conditions existed at the site; this represents about 28% on wind loading. If the site roughness had been smoother than that upwind, this effect of roughness change would have been reversed.

TABLE 6.1 CALCULATION SHEET 3
Calculation of Maximum Gust Speed at a Site Downwind of Two Changes in Surface Roughness



1	Site			$\phi = 52°$
2	Wind direction, θ (if known)			–
3	V_r	Reference (or map)	m/s	22
4	z_r	mean-hourly	m	10
5	z_{0r}	wind speed	m	0.01
6	T_r	(see 82026[4])	yrs	50
7	$P_{Nr} = 1 - (1 - 1/(6))^{50}$		$(N_r = 50)$	0.636
8	P_N	design		0.05
9	N	values	yrs	50
10	K_{Nr}	Eqn 5.2	of 82026[4]	1.0
11	K_N	or Fig. 2		1.155
12	$f = 1.458 \times 10^{-4} \sin\phi$		rad/s	1.15×10^{-4}

13	$K_{z*r} = 2.5\ln[(4)/(5)]$			17.27
14	$u_{*r} = [(3)/(13)][11/(10)]$		m/s	1.471
15	z_0	Sect. 6.1 and	m	0.5
16	z_{01}	Table 13.1 of	m	0.1
17	z_{02}	82026[4]	m	0.001
18	d at site (Fig. 3 of 82026)		m	20
19	$K_{s*} = \ln(10^5/(5))/\ln(10^5/(15))$			1.320
20	$K_{s*1} = \ln(10^5/(5))/\ln(10^5/(16))$			1.167
21	$K_{s*2} = \ln(10^5/(5))/\ln(10^5/(17))$			0.875
22	$u_* = (14) \times (19)$		m/s	1.942
23	$u_{*1} = (14) \times (20)$		m/s	1.717
24	$u_{*2} = (14) \times (21)$		m/s	1.287

25	$\lvert\ln(z_{01}/z_{02})\rvert$		4.605
26	$\lvert\ln(z_0/z_{01})\rvert$		1.609
27	$[u_{*1}/(fz_{01})]^n = [23/\{(12) \times (16)\}]^{n\,\dagger}$		15.49
28	$[u_*/(fz_0)]^n = [22/\{(12) \times (15)\}]^{n\,\dagger\dagger}$		11.00
29	$R_1 = (25)/(27)$		0.297
30	$R = (26)/(28)$		0.146
31	$x_1 + x$	m	4000
32	x	m	1000
33	K_{x1} for R_1, $(x_1 + x)$ Fig. 4 †		1.15
34	K_x for R, x (Fig. 4)††		1.13
35	Gust duration, τ	s	3
36	$\hat{K}_{x1}$ (Fig. 3)		1.07
37	$\hat{K}_x$ (Fig. 3))		1.06

† For $z_{01} > z_{02}$, $n = 0.23$, use Fig. 4a to obtain K_{x1}; for $z_{01} < z_{02}$, $n = 0.14$, use Fig. 4b to obtain K_{x1}.

†† For $z_0 > z_{01}$, $n = 0.23$, use Fig. 4a for K_x; for $z_0 < z_{01}$, $n = 0.14$, use Fig. 4b for K_x.

38	z (measured from zero plane) at site	m	20	40	60	80	100	150	200		
39	Height from ground = (38) + (18)	m	40	60	80	100	120	170	220		
40	K_{z*} for z_0, u_*, z — Fig. 6 or		9.32	11.16	12.28	13.10	13.76				
41	K_{z*1} for z_{01}, u_{*1}, z — Eqn (A1.8)		13.36	15.21	16.34	17.17	17.85				
42	K_{z*2} for z_{02}, u_{*2}, z — of 82026[4]		24.91	26.80	27.97	28.84	29.55	30.95	32.06		
43	$V_z = V_A = (22) \times (40)$	m/s	18.10	21.67	23.85	25.44	26.72				
44	$V_{z1} = V_B = (23) \times (41)$	m/s	22.94	26.12	28.06	29.48	30.65				
45	$V_{z2} = V_C = (24) \times (42)$	m/s	32.06	34.49	36.00	37.12	38.03	39.83	41.26		
46	I_u (Fig. 1 for z, z_0)		0.269	0.239	0.223	0.211	0.202				
47	I_{u1} (Fig. 1 for z, z_{01})		0.197	0.180	0.169	0.160	0.152				
48	I_{u2} (Fig. 1 for z, z_{02})		0.114	0.103	0.094	0.088	0.082	0.071	0.064		
49	K_τ (Fig. 2 for τ, I_u)		1.82	1.73	1.68	1.65	1.62				
50	$K_{\tau1}$ (Fig. 2 for τ, I_{u1})		1.60	1.55	1.52	1.49	1.47				
51	$K_{\tau2}$ (Fig. 2 for τ, I_{u2})			1.32	1.29	1.27	1.25	1.22	1.20		
52	$\hat{V}_{xA} = (36) \times (37) \times (43) \times (49)$	m/s	37.4	42.5	45.4	47.6	49.1				
53	$[\hat{V}_{xA}]_1 = (36) \times (44) \times (50)$	m/s	39.3	43.3	45.6	47.0	48.2				
54	$[\hat{V}_{xA}]_2 = (45) \times (51)$	m/s		45.5	46.4	47.1	47.5	48.6	49.5		
55	$\hat{h}_i = z$ at which (52) = (53)	m	≈ 60								
56	$\hat{h}_{i1} = z$ at which (53) = (54)	m	≈ 80								
57	$\hat{V}_{zx}$ at site. For $z \le \hat{h}_i$, $\hat{V} = (52)$. For $\hat{h}_i \le z \le \hat{h}_{i1}$, $\hat{V} = (53)$. For $z \ge \hat{h}_{i1}$, $\hat{V} = (54)$.										
58	$\hat{V}_{zx}$ at site	m/s	37.4	42.5	45.4	47.0	47.5	48.6	49.5		

7. REFERENCES AND DERIVATION

7.1 References

The References given are recommended sources of information supplementary to that in this Data Item.

1.	ESDU	Characteristics of atmospheric turbulence near the ground. Part II: single point data for strong winds (neutral atmosphere). Item No. 85020, ESDU International, London, 1985.
2.	ESDU	Computer program for wind speeds and turbulence properties: flat or hilly sites in terrain with roughness changes. Item No. 01008, and VIEWpac program E0108, ESDU International, 2001. (This Item supersedes Item No. 92032).
3.	HARRIS, R.I.	The classification of structures for the assessment and codification of wind effects. Proc. of 5th Int. Conf. on Wind Engineering, Colorado, USA, Vol. 2, pp.1257–1270. Pergamon Press, 1980. (*Alternative source*: Paper 11 of Proc. CIRIA Conf. on “Wind engineering in the eighties”, CIRIA, London, 1981.)
4.	ESDU	Strong winds in the atmospheric boundary layer. Part 1: hourly-mean wind speeds. Item No. 82026, ESDU International Ltd, London, 1982.

7.2 Derivation

The Derivation lists selected sources that have assisted in the preparation of this Data Item.

5.	DEACON, E.L.	Gust variation with height up to 150 m. *Q. J. Roy. Met. Soc*., Vol. 81, No. 350, pp.562–573, October 1955.
6.	DURST, C.S.	Wind speeds over short periods of time. *Met. Mag*., Vol. 89, No. 1056, pp.181–186, July 1960.
7.	DAVENPORT, A.G.	Note on the distribution of the largest value of a random function with application to gust loading. *Proc. I. Civil Engrs*, Vol. 22, pp.187–196, August 1964.
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9.	WIERINGA, J.	Gust factors over open water and built-up country. *Boundary-Layer Meteorol*., Vol. 3 pp.424–441, 1973.
10.	GREENWAY, M.E.	An analytical approach to wind velocity gust factors. *J. Indust. Aerodyn*., Vol. 5, pp.61–92, October 1979.
11.	GREENWAY, M.E.	The effects of finite observation time and finite averaging time on the R.M.S. and extreme wind velocity. *J. Wind Engng Indust. Aerodyn*., Vol. 6, pp.175–180, 1980.
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13.	WILLS, J.A.B.	The measurement of wind structure at West Sole. NMI Rep. R 79 (OT-R-8039), National Maritime Institute, UK, June 1980.
14.	DEAVES, D.M.	Computations of wind flow over changes in surface roughness. *J. Wind Engng Indust. Aerodyn*., Vol. 7, pp.65–94, 1981.
15.	DEAVES, D.M.	Terrain-dependence of longitudinal r.m.s. velocities in the neutral atmosphere. *J Wind Engng Indust. Aerodyn*., Vol. 8, pp.259–274, 1981.
16.	WOOD, C.J.	A simplified calculation method for gust factors. *J. Wind Engng Indust. Aerodyn*., Vol. 12, No. 3, pp.385–388, 1983.

8. CALCULATION SHEETS

TABLE 8.1 Calculation Sheet 1
Calculation of Maximum Gust Speed at a Site With No Change in Surface Roughness Upwind (Equilibrium Conditions)

1	Site									
2	Wind direction, θ (if known)									
3	V_r	Reference (or map)	m/s							
4	z_r	hourly -mean wind	m							
5	z_{0r}	speed; see	m							
6	T_r	Item 82026[4]	yrs							
7	$P_{Nr} = 1-(1-1/(6))^{50} \quad (N_r = 50)$									
8	P_N	design								
9	N	values	yrs							
10	K_{Nr}	Fig. 2 or — of 82026[4]								
11	K_N	Eqn (5.2) — of 82026[4]								
12	$f = 1.458 \times 10^{-4} \sin\phi$		rad/s							
13	$K_{z*r} = 2.5\ln[(4)/(5)]$									
14	$u_{*r} = [(3)/(13)][(11)/(10)]$		m/s							
15	z_0 (Table 13.1 of 82026[4])		m							
16	d at site (Fig. 3 of 82026[4])		m							
17	$K_{s*} = \ln(10^5/(5))/\ln(10^5/(15))$									
18	$u_* = (14) \times (17)$		m/s							
19	z (measured from zero plane) at site		m							
20	$z + d = (19) + (16) =$ height from ground		m							
21	K_{z*} for z_0, u_*, z (Fig. 6 of 82026)									
22	$V_z = (18) \times (21)$		m/s							
23	Gust duration, τ		s							
24	I_u (Fig. 1 for z, z_0)									
25	K_τ (Fig. 2 for τ, I_u)									
26	$\hat{V}_z = (22) \times (25)$		m/s							

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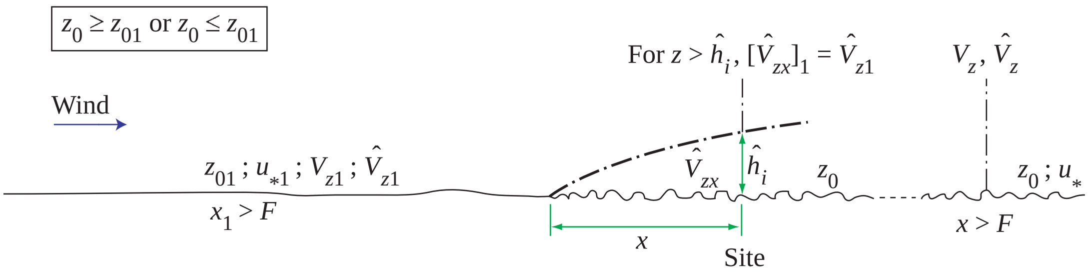
TABLE 8.2 Calculation Sheet 2
Calculation of Maximum Gust Speed at a Site Downwind of a Sudden Change in Surface Roughness



1	Site			15	z_0 Sect. 6.1 of 82026	m	
2	Wind direction, θ (if known)			16	z_{01} Table 3.1 of 82026	m	
3	V_r Reference (or map)	m/s		17	d at site (Fig. 3 of 82026)	m	
4	z_r hourly-mean	m		18	$K_{s*} = \ln(10^5/(5))/\ln(10^5/(15))$		
5	z_{0r} wind speed	m		19	$K_{s*1} = \ln(10^5/(5))/\ln(10^5/(16))$		
6	T_r (see 82026[4])	yrs		20	$u_* = (14) \times (18)$	m/s	
7	$P_{Nr} = 1 - (1 - 1/(6))^{50}$	(N_r = 50)		21	$u_{*1} = (14) \times (19)$	m/s	
8	P_N design			22	$\lvert\ln(z_0/z_{01})\rvert = \lvert\ln[(15)/(16)]\rvert$		
9	N values	yrs		23	$[u_*/(fz_0)]^n = [(20)/((12) \times (15))]^n$ †		
10	K_{Nr} Fig. 2 or of 82026[4]			24	$R = (22)/(23)$		
11	K_N Eqn (5.2) of 82026[4]			25	x	m	
12	$f = 1.458 \times 10^{-4} \sin\phi$	rad/s		26	K_x for R and x (Fig. 4a or 4b)		
13	$K_{z_*r} = 2.5\ln[(4)/(5)]$			27	Gust duration, τ	s	
14	$u_{*r} = [(3)/(13)][(11)/(10)]$	m/s		28	$\hat{K}_x$ (Fig. 3)		

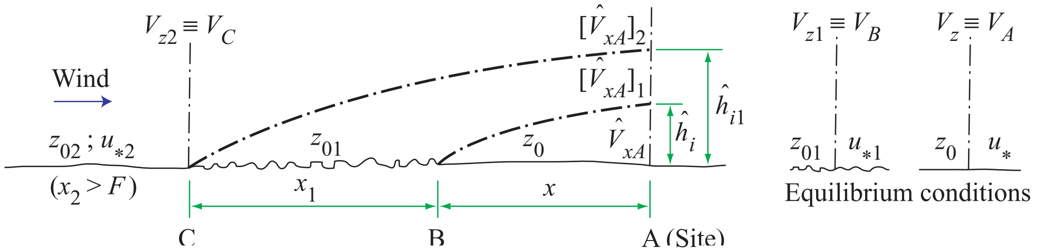
† For $z_0 > z_{01}$, $n = 0.23$; for $z_0 < z_{01}$, $n = 0.14$

n.b. $\ln \equiv \log_e$

29	z (mesured from zero plane) at site	m							
30	$z + d = (29) + (17)$ = height from ground	m							
31	K_{z_*} for z_0, u_*, z — Fig. 6 or Eqn (A1.8) of 82026								
32	$K_{z_{*1}}$ for z_{01}, u_{*1}, z — Fig. 6 or Eqn (A1.8) of 82026								
33	$V_z = (20) \times (31)$ Values for $x > F$	m/s							
34	$V_{z1} = (21) \times (32)$ Values for $x > F$	m/s							
35	I_u (Fig. 1 for z_0)								
36	I_{u1} (Fig. 1 for z_{01})								
37	K_τ (Fig. 2 for τ, I_u)								
38	$K_{\tau 1}$ (Fig. 2 for τ, I_{u1})								
39	$(28) \times (33) \times (37) = \hat{V}_{zx}$	m/s							
40	$(34) \times (38) = [\hat{V}_{zx}]_1$	m/s							
41	$\hat{h}_i\{= z$ at which $(39) = (40)\}$	m							
42	$\hat{V}_{zx}$ at site = (39) for $z \leq (41)$	m/s							
	= (40) for $z \geq (41)$	m/s							

TABLE 8.3 Calculation Sheet 3

Calculation of Maximum Gust speed at a Site Downwind of Two Changes in Surface Roughness



1	Site		13	$K_{z*r} = 2.5\ln[(4)/(5)]$		25	$\lvert\ln(z_{01}/z_{02})\rvert$	
2	Wind direction, θ (if known)		14	$u_{*r} = [(3)/(13)][11/(10)]$ m/s		26	$\lvert\ln(z_0/z_{01})\rvert$	
3	V_r Reference (or map) m/s		15	z_0 Sect. 6.1 and m		27	$[u_{*1}/(fz_{01})]^n = [(23)/\{(12)\times(16)\}]^n$ †	
4	z_r hourly-mean m		16	z_{01} Table 13.1 of m		28	$[u_*/(fz_0)]^n = [(23)/\{(12)\times(15)\}]^n$ ††	
5	z_{0r} wind speed m		17	z_{02} 82026[4] m		29	$R_1 = (25)/(27)$	
6	T_r (see 82026[4]) yrs		18	d at site (Fig. 3 of 82026) m		30	$R = (26)/(28)$	
7	$P_{Nr} = 1-(1-1/(6))^{50}$ ($N_r = 50$)		19	$K_{s*} = \ln(10^5/(5))/\ln(10^5/(15))$		31	$x_1 + x$ m	
8	P_N design		20	$K_{s*1} = \ln(10^5/(5))/\ln(10^5/(16))$		32	x m	
9	N values yrs		21	$K_{s*2} = \ln(10^5/(5))/\ln(10^5/(17))$		33	K_{x1} for R_1, $(x_1 + x)$ Fig. 4 †	
10	K_{Nr} Eqn 5.2 of 82026[4]		22	$u_* = (14)\times(19)$ m/s		34	K_x for R, x (Fig. 4)††	
11	K_N or Fig. 2		23	$u_{*1} = (14)\times(20)$ m/s		35	Gust duration, τ s	
12	$f = 1.458\times10^{-4}\sin\phi$ rad/s		24	$u_{*2} = (14)\times(21)$ m/s		36	$\hat{K}_{x1}$ (Fig. 3)	
						37	$\hat{K}_x$ (Fig. 3))	

† For $z_{01} > z_{02}$, $n = 0.23$, use Fig. 4a to obtain K_{x1}; for $z_{01} < z_{02}$, $n = 0.14$, use Fig. 4b to obtain K_{x1}.

†† For $z_0 > z_{01}$, $n = 0.23$, use Fig. 4a for K_x; for $z_0 < z_{01}$, $n = 0.14$, use Fig. 4b for K_x.

38	z (measured from zero plane) at site m									
39	Height from ground = (38) + (18) m									
40	K_{z*} for z_0, u_*, z Fig. 6 or									
41	K_{z*1} for z_{01}, u_{*1}, z Eqn (A1.8)									
42	K_{z*2} for z_{02}, u_{*2}, z of 82026[4]									
43	$V_z = V_A = (22)\times(40)$ m/s									
44	$V_{z1} = V_B = (23)\times(41)$ m/s									
45	$V_{z2} = V_C = (24)\times(42)$ m/s									
46	I_u (Fig. 1 for z, z_0)									
47	I_{u1} (Fig. 1 for z, z_{01})									
48	I_{u2} (Fig. 1 for z, z_{02})									
49	K_τ (Fig. 2 for τ, I_u)									
50	$K_{\tau1}$ (Fig. 2 for τ, I_{u1})									
51	$K_{\tau2}$ (Fig. 2 for τ, I_{u2})									
52	$\hat{V}_{xA} = (36)\times(37)\times(43)\times(49)$ m/s									
53	$[\hat{V}_{xA}]_1 = (36)\times(44)\times(50)$ m/s									
54	$[\hat{V}_{xA}]_2 = (45)\times(51)$ m/s									
55	$\hat{h}_i = z$ at which $(52) = (53)$ m									
56	$\hat{h}_{i1} = z$ at which $(53) = (54)$ m									
57	$\hat{V}_{zx}$ at site. For $z \le \hat{h}_i$, $\hat{V} = (52)$. For $\hat{h}_i \le z \le \hat{h}_{i1}$, $\hat{V} = (53)$. For $z \ge \hat{h}_{i1}$, $\hat{V} = (54)$.									
58	$\hat{V}_{zx}$ at site m/s									

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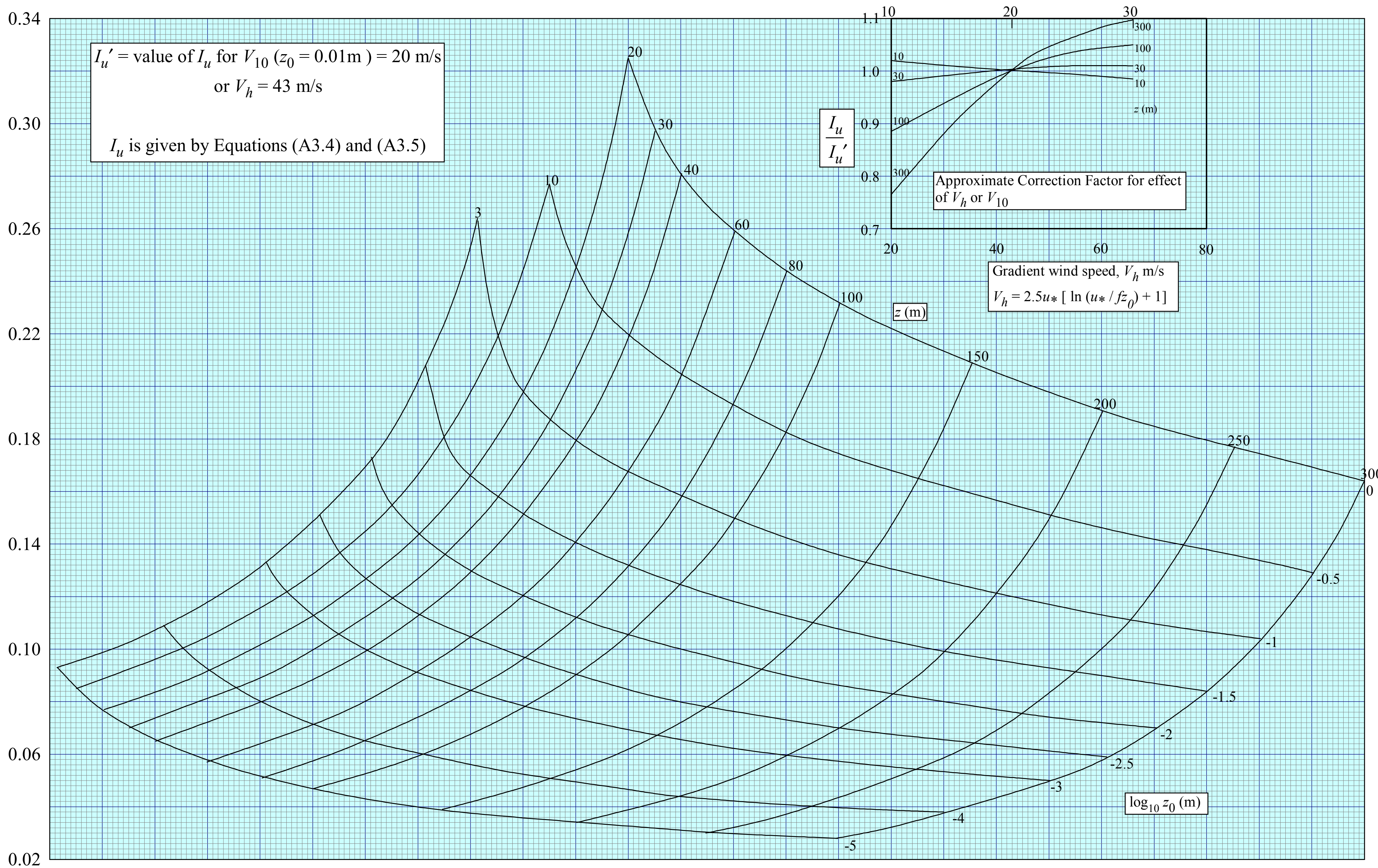

FIGURE 1 TURBULENCE INTENSITY FOR EQUILIBRIUM CONDITIONS

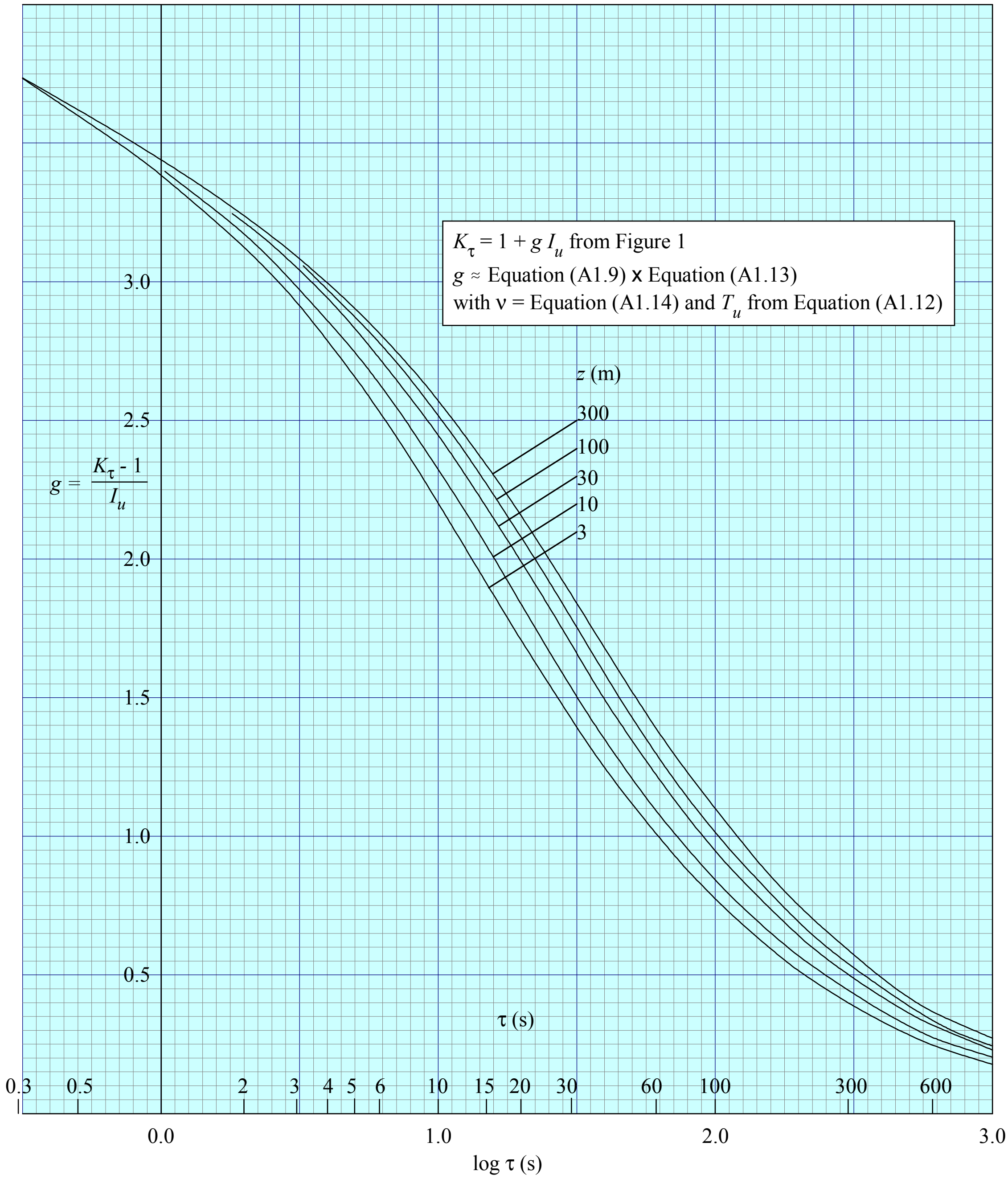

FIGURE 2a Peak factor, g, for T_0 = 3600 s

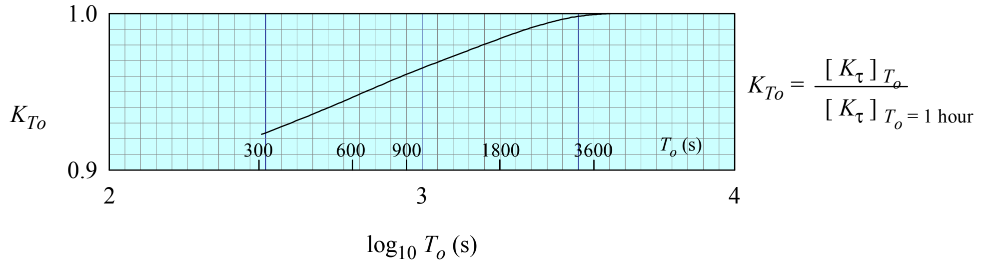

FIGURE 2b Effect on K_τ of T_0 < 3600 s

FIGURE 2 PEAK AND GUST FACTORS

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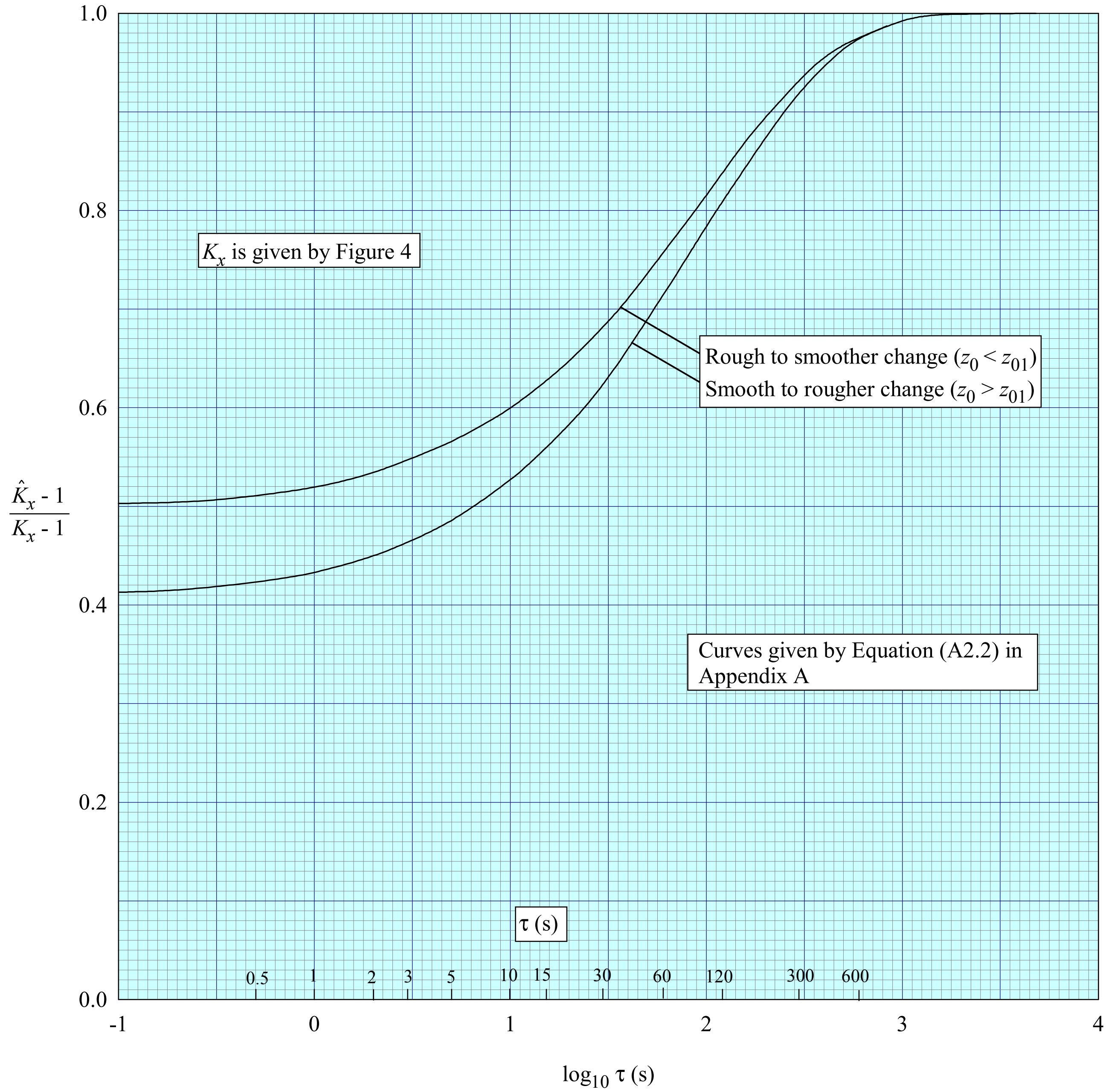

FIGURE 3 THE FETCH FACTOR $\hat{K}_x$ FOR GUSTS

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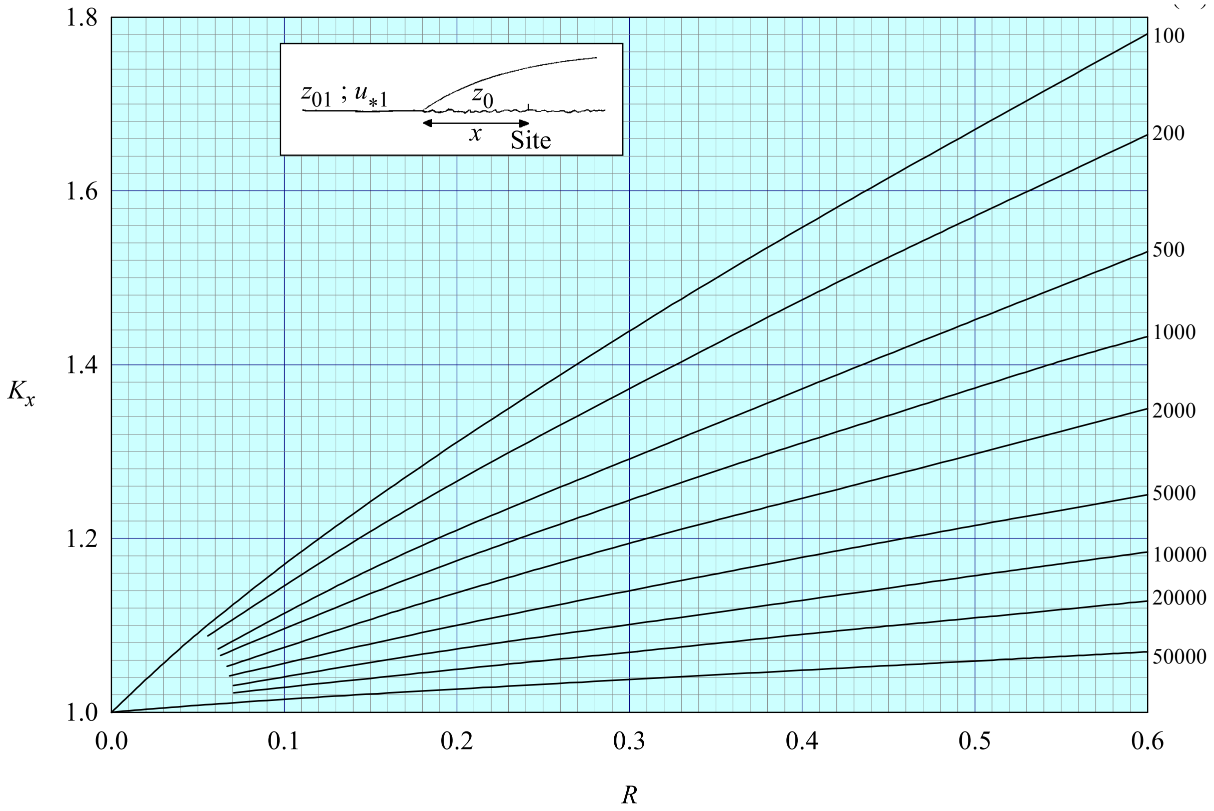
FIGURE 4a Smooth-to-rougher change ($z_0 > z_{01}$)



$$R = \frac{|\ln(z_0 / z_{01})|}{[u_* / (f z_0)]^n} \qquad \begin{array}{l} n = 0.23 \text{ for } z_0 > z_{01} \\ n = 0.14 \text{ for } z_0 < z_{01} \end{array}$$

K_x given by Equations (A2.2) or (A2.3) in ESDU 82026

FIGURE 4b Rough-to-smoother change ($z_0 < z_{01}$)

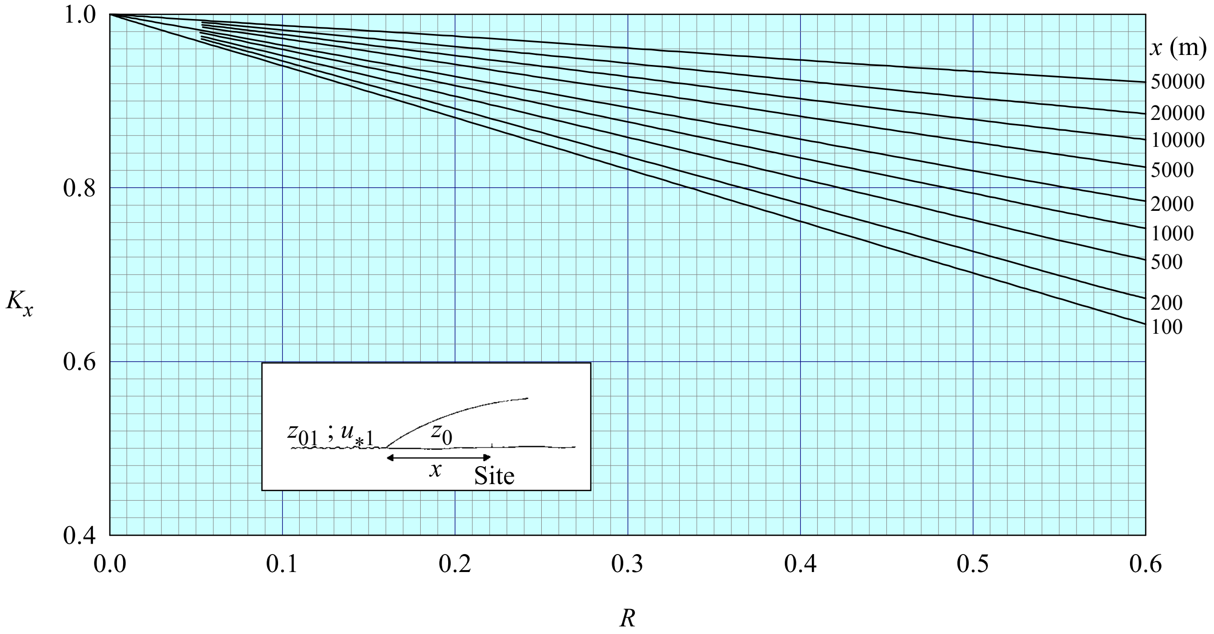


FIGURE 4 THE FETCH FACTOR, K_x FOR HOURLY-MEAN WIND SPEEDS

APPENDIX A BASIS OF THE DATA

A1. THE GUST FACTOR, K_τ

The instantaneous wind velocity is given by $V(t) = V + u(t)$. The maximum value occuring in a given observation period, T_o, (usually taken as 3600 s) averaged over a short period τ seconds can be related to the equivalent hourly-mean wind speed, (V_z) by an expression of the form

$$K_\tau = \frac{\hat{V}_z(\tau, T_o)}{V_z} = \frac{V_z + \hat{u}(\tau, T_o)}{V_z} = 1 + g\frac{\sigma_u}{V_z} \tag{A1.1}$$

where
$$g = \frac{\hat{u}(\tau, T_o)}{\sigma_u(\tau, T_o)} \cdot \frac{\sigma_u(\tau, T_o)}{\sigma_u}. \tag{A1.2}$$

The peak factor, g, is dependent on the properties of the u-component of turbulence, the averaging time τ and the observation period T_o. In past analyses the peak factor g has been obtained principally by empirical analysis of gust measurements at different sites. A more satisfactory approach is to use the spectral density of the u-component of turbulence to derive an extreme value distribution of the fluctuating velocity component (averaged over finite time τ) from which, for example, the expected (mean) maximum value $\hat{u}(\tau, T_o)$, can be derived for a given observation period T_o. The derivation of the terms in Equation (A1.2) using this approach is described in Sections A1.1 and A1.2. The derivation of the turbulence intensity parameter, $I_u = \sigma_u / V_z$, in Equation (A1.1) which then gives K_τ is described in Section A3.

A1.1 The Effect of Finite τ and T_o on the Properties of Turbulence

The effect of finite averaging time, τ, and finite observation period, T_o, on the spectrum of $u(t)$ is to effectively confine the spectrum $S_u(n)$ to a 'spectral window' truncated at some low frequency (depending on T_o) and at some high frequency (dependent on τ) as illustrated in Sketch A1.1. This tends to remove the less rapid and more rapid fluctuations and, in effect, imposes a filter (ψ) on the spectrum so that the variance $\sigma_u^2(\tau, T_o)$ is given by

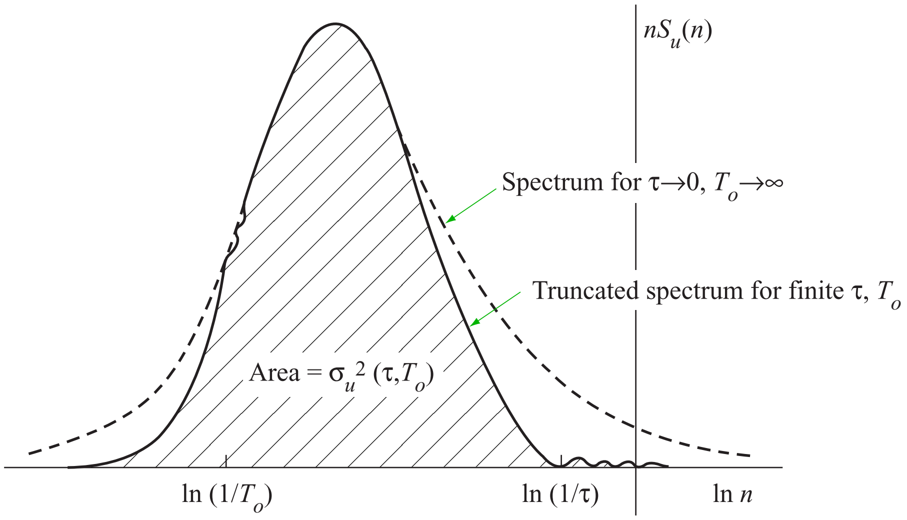
$$\int_0^\infty S_u(n, \tau, T_o)\mathrm{d}n = \int_0^\infty S_u(n) \cdot \psi(n, \tau, T_o)\mathrm{d}n = \sigma_u^2(\tau, T_o) \tag{A1.3}$$

where
$$\psi(n, \tau, T_o) = \frac{\sin^2(\pi n \tau)}{(\pi n \tau)^2} - \frac{\sin^2(\pi n T_o)}{(\pi n T_o)^2}. \tag{A1.4}$$

Equation (A1.3) can be written in the form, illustrated in Sketch A1.1,

$$\int_{-\infty}^{\infty} n S_u(n) \psi \mathrm{d}(\ln n) = \sigma_u^2(\tau, T_o) \tag{A1.5}$$

and, with an appropriate expression for $S_u(n)$, values of $\sigma_u(\tau, T_o)/\sigma_u$ can then be derived as explained in the following Section.



Sketch A1.1 Illustration of truncated spectrum when $\dfrac{T_o}{\tau}$ is large

A1.2 The Peak Factor *g*

Assuming that the time-averaged fluctuating velocity, $u(\tau, T_o)$, is a Gaussian random variable, and that its extreme value distribution is of the Fisher-Tippett Type 1 form, then an expression for the expected maximum value, $\hat{u}(\tau, T_o)$, can be derived. The Fisher-Tippett type 1 distribution is given by

$$\hat{u} = u_m + \frac{1}{a}[-\ln(-\ln(1 - \hat{P}_1))] \tag{A1.6}$$

where $\hat{P}_1$ is the probability that $u(\tau, T_o)$ will be equal to or greater than a value of $\hat{u}$ in a period T_o. Davenport[5] shows that the mode (u_m) and dispersion $(1/a)$ parameters are given by

$$\frac{u_m}{V} = \frac{\sigma_u(\tau, T_o)}{V}\sqrt{2\ln[T_o v(\tau, T_o)]}, \tag{A1.7}$$

$$\frac{1}{aV} = \frac{\sigma_u(\tau, T_o)}{V}\bigg/\sqrt{2\ln[T_o v(\tau, T_o)]} \tag{A1.8}$$

and that the mean of the maximum values is given by

$$\frac{\hat{u}(\tau, T_o)}{\sigma_u(\tau, T_o)} = \sqrt{2\ln[T_o v(\tau, T_o)]} + \frac{0.577}{\sqrt{2\ln[T_o v(\tau, T_o)]}} \tag{A1.9}$$

which represents a probability of $\hat{P}_1 = 0.570$ of $\hat{u}(\tau, T_o)$ being exceeded*. In Equation (A1.9), $v(\tau, T_o)$ is the zero crossing rate derived from the filtered spectrum $S_u(n, \tau, T_o) = S_u(n) \cdot \psi(n, \tau, T_o)$ and is given by

$$v^2(\tau, T_o) = \frac{\int_0^\infty n^2 S_u(n, \tau, T_o)\,dn}{\int_0^\infty S_u(n, \tau, T_o)\,dn}. \tag{A1.10}$$

* Since the probability distribution of the extreme values is very narrow, the probability of significantly larger values than the mean maximum-value occurring is small.

Using the expression for $S_u(n)$ of the von Karman form

$$\frac{nS_u(n)}{\sigma_u^2} = \frac{4nT_u}{[1 + 70.8(nT_u)^2]^{5/6}} \tag{A1.11}$$

(where $T_u = {}^xL_u/V$ is the integral time scale of turbulence) Equations (A1.5) and (A1.10) have been evaluated numerically to obtain $\sigma_u(\tau,T_o)/\sigma_u$ and $\nu(\tau,T_o)$ for various values of τ and T_o. These data, together with Equations (A1.9) and (A1.2) give the values of $g = (K_\tau - 1)/I_u$ plotted in Figure 2 for $T_o = 1$ hour and for $K_{To} = \hat{V}(\tau,T_o)/\hat{V}(\tau,T_o = 1\text{ hour})$ in Figure 2b. It is found that the gust factor is only weakly dependent on the integral time scale parameter, T_u. Thus, in evaluating Figure 2, an approximate relationship between T_u and z was used derived from data in Item Nos 85020[1] and 82026[4] for ${}^xL_u$ and V_z which shows that to a sufficiently close approximation for the range of wind speeds of interest, and independent of terrain roughness,

$$T_u = 3.13z^{0.2} \text{ seconds.} \tag{A1.12}$$

A1.3 Equation Fit to Figure 2

Greenway[10,11] has produced analytical solutions to Equations (A1.5) and (A1.10) for $\sigma_u(\tau,T_o)/\sigma_u$ and $\nu(\tau/T_o)$. These theoretical solutions involve of Bessel and Struve functions and, subsequently, Wood[16] has derived a much simpler empirical fit to these equations which apply for $T_o = 3600$ s and $\tau < 300$ s. Wood's equations are

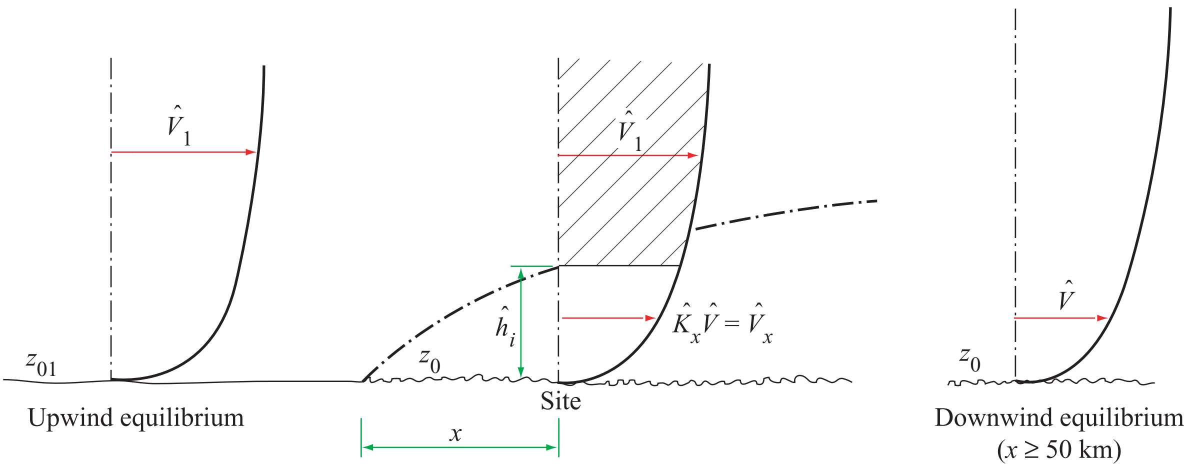
$$\frac{\sigma_u(\tau,T_o = 1\text{ hr})}{\sigma_u} = 1 - 0.193\left[\frac{T_u}{\tau} + 0.1\right]^{-0.68}, \tag{A1.13}$$

$$\nu(\tau,T_o = 1\text{ hr}) = [0.007 + 0.213(T_u/\tau)^{0.654}]/T_u \tag{A1.14}$$

which together with Equations (A1.9) and (A1.2) give the values of g which are between 0 and about 5% higher than the values in Figure 2; this error has a negligible effect on K_τ.

A2. THE FETCH FACTOR, $\hat{K}_x$, FOR GUSTS

In the general case, the local gust factor, $\hat{V}_{zx}/V_{zx}$, a distance x downwind of a sudden change in terrain roughness is required where equilibrium boundary layer conditions are assumed to exist upwind of the roughness change as illustrated in Sketch A2.1.



Sketch A2.1 Single step change in terrain roughness

The local gust factor can be obtained from Equation (A1.1) but using the local value of I_{ux}. The means for estimating $I_{ux} = \sigma_{ux}/V_x$ for a site such as illustrated in Sketch A2.1 is described in Section A3. However, this method, although relatively simple to apply, is tedious. To simplify the estimation of $\hat{V}_z$ a series of computations were made for various combinations of roughness changes for a range of τ, z and x. A similar result to that derived in Item No. 82026 for hourly-mean wind speeds was found applicable in that, within an inner layer originating from the step change in roughness (Sketch A2.1), the gust fetch factor defined as

$$\hat{K}_x = \frac{\hat{V}_{zx}}{\hat{V}_z} = \frac{\hat{V}_{zx}}{V_z K_\tau} \tag{A2.1}$$

is independent of z for $z \le h_i$ to within about $\pm 3\%$ for a given gust duration, τ, and is insensitive to the value of the gradient wind speed. The gust factor, K_τ, is defined as the ratio $\hat{V}_z / V_z$ that would occur for equilibrium boundary-layer conditions over the site roughness z_0 (i.e. for $x \ge 50$ km). For $z > \hat{h}_i$ the gust profile is the same as that in the upwind eqilibrium boundary layer over roughness z_0; the height $\hat{h}_i$ is thus given by the value of z where $\hat{K}_x K_\tau V_z = \hat{V}_{z1} = V_z K_{\tau 1}$.

For a given gust duration τ, values of the factor $\hat{K}_x$ were found to vary in a similar manner to those of the corresponding fetch factor $K_x = V_{zx}/V_z$ for hourly-mean wind speeds derived in item No. 82026. The general relationship was found that

$$\frac{\hat{K}_x - 1}{K_x - 1} = 1 - a \exp[-0.05\tau^{0.65}] \tag{A2.2}$$

where $a = 0.595$ for smooth-to-rougher terrain changes and $a = 0.502$ for rough-to-smoother terrain changes. Equation (A2.2) is applicable for all values of τ and forms the basis of the data presented in Figure 3.

A3. TURBULENCE INTENSITY

A theoretical method that takes into account the effect on hourly-mean speed and on σ_u of a change in surface roughness upwind of the site in question has been derived by Deaves[14,15]. The results of this method were used[15] to correct site measurements to equivalent equilibrium values where there are known changes in terrain roughness upwind of the measuring site. It is then found that the maximum value of σ_u/u_* for equilibrium conditions corresponding to various values of z_0, is a constant to within about $\pm 5\%$. Whilst there are few reliable data for built-up terrain $(z_0 > 0.1 \text{ m})$ with which to check the validity of the terrain-independence of $[\sigma_u/u_*]_{max}$ over the complete range of z_0, it seems probable that this result should hold true *for an equilibrium boundary layer.*

Harris and Deaves[12] have derived an empirical equation to represent the variation of σ_u/u_* with height which is consistent with appropriate scaling laws within the atmospheric boundary layer. This equation is

$$[\sigma_u/u_*]_x = 2.63\eta[0.538 + 0.09\ln(z/z_0)]^m \tag{A3.1}$$

where $m = \eta^{16}$,

$\eta = 1 - z/h_x$,

and $h_x = u_{*x}/(6f)$

and σ_{ux} and u_{*x} are local values within the internal boundary layer (originating a distance x upwind) of height $h_x = u_{*x}/(6f)$. Because Equation (A3.1) is based partly on data for non-equilibrium conditions it does not give a constant value of $[\sigma_u/u_*]_{max}$ independent of z_0 as suggested should apply by the preceding discussion for an equilibrium boundary layer. However, it is based to a large extent on high quality measurements $(\tau \to 0)$ giving values of σ_u/u_* for the Rugby site $z_0 = 0.03$ m where it can be assumed that equilibrium conditions exist and that Equation (A3.1) applies. The variation of $[\sigma_u/u_*]_{max}$

with z_0 built into Equation (A3.1) is based on measurements from other smoother, and rougher, sites where equilibrium conditions clearly do not exist; this variation is given to a close approximation by

$$\left[\frac{\sigma_u}{u_*}\right]_{x,max} = 1 + 0.156 \ln [u_*/(fz_0)] \tag{A3.2}$$

which for the Rugby site gives $[\sigma_u/u_*]_{max} = 2.85$. thus, a more correct form of Equation (A3.1) appropriate to equilibrium conditions is obtained by factoring this equation by the ratio $2.85/[1 + 0.156 \ln(u_*/(fz_0))]$ so that

$$\frac{\sigma_u}{u_*} = \frac{7.5\eta[0.538 + 0.09 \ln(z/z_0)]^{\eta^{16}}}{1 + 0.156 \ln(u_*/(fz_0))} \tag{A3.3}$$

where $\eta = 1 - 6fz/u_*$. For all sites with equilibrium conditions the maximum value of σ_u/u_* is then approximately 2.85 although the height at which this maximum occurs will vary, as expected, with z_0.

For equilibrium boundary layer conditions the intensity of turbulence is then given by

$$I_u = \frac{\sigma_u}{V_z} = \frac{\sigma_u}{u_*} \cdot \frac{u_*}{V_z}, \tag{A3.4}$$

where V_z/u_* is given by Equation (A1.8) in Item No. 82026, and this forms the basis for the data in Figure 1.

The intensity, I_u, is weakly dependent on wind speed; the values presented in Figure 1 are for a gradient wind speed corresponding to a value of $V_{10} = 20$ m/s for $z_0 = 0.01$ m. A separate, approximate, correction factor for other wind speeds is provided in Figure 1 which shows that for most strong winds I_u can be considered independent of wind speed within the uncertainty of the data (approximately ± 10 %).

A3.1 Non-equilibrium Effects

For a non-equilibrium boundary layer the method of Deaves[15] provides a means of estimating the ratio of σ_{ux}/σ_u where σ_{ux} relates to a site (z_0) which is a distance x downwind of a roughness change z_{01} to z_0, and σ_u relates to equilibrium conditions over roughness z_0. The method is based on a solution of the Navier-Stokes equations using a simplified turbulence closure model. The results of this method, which are in general agreement with other authors, have been used as a basis for calculating the local intensity of turbulence which is given by

$$I_{ux} = \frac{\sigma_{ux}}{\sigma_u}\frac{\sigma_u}{u_*}\frac{u_*}{V_z}\frac{V_z}{V_{zx}}. \tag{A3.5}$$

Values of σ_u/u_* are given by Equation (A3.3) and values of V_z/u_* and $V_{zx}/V_z = K_x$ are given by graphs or equations in Item No. 82026. Values of $\hat{V}_{zx}$ can then be obtained from Equation (A1.1) using local values of I_{ux} and V_{zx} instead of I_u and V_z. From these basic data, values of $\hat{K}_x = \hat{V}_{zx}/(V_z K_\tau)$ were then derived which form the basis of the simplified method described in Section A2.

Values of I_{ux} are not included explicitly in this Item since in the simplified method (whereby $\hat{V}_{zx} = K_\tau \hat{K}_x V_z$) the gust factor K_τ is dependent on I_u and the non-equilibrium effect on turbulence intensity is incorporated in the derivation of the gust fetch factor $\hat{K}_x$.

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83045

Strong winds in the atmospheric boundary layer. Part 2: discrete gust speeds
ESDU 83045

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ESDU 83045 gives a method for estimating the variation of the expected maximum gust speed with height above the ground for any gust averaging time greater than about 1 second. The method takes into account the roughness of the site terrain and also any roughness changes that occur upwind. The roughness of the terrain affects the hourly-mean wind speed and its turbulence component. Theoretical methods were used to account for these effects and the results combined into a simplified method that is presented in the form of convenient calculation sheets and equations for the data. A gust factor approach is used to relate the maximum gust speed to the corresponding hourly-mean wind speed given by ESDU 82026.The gust facor dependence on averaging time is derived using the spectral density of the fluctuating component of wind speed. The approach assumes an extreme-value distribution that provides an estimate of the maximum value of the fluctuating component and hence the gust speed for any averaging time and time interval within which the wind speed is observed. Gust factors derived using this approach are presented graphically and in simplified equation form. A practical worked example illustrates the use of the data.

The full methods for estimating the effects on gust speed of terrain roughness changes, height above ground and averaging time are built into the computer program VIEWpac E0108 described in ESDU 01008.

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