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Supersedes in part
Item No. 72026

Strong winds in the atmospheric boundary layer
Part 1: hourly-mean wind 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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ESDU Engineering Sciences Data Unit

82026

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 $q = ½\ \rho V^2$ respectively (see Section A3, Appendix A)	$(m/s)^{-1}$ and $(kN/m^2)^{-1}$
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)	
$\left.\begin{array}{l}K_s\\K_{s*}\end{array}\right\}$	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)	
$\left.\begin{array}{l}K_z\\K_{z*}\end{array}\right\}$	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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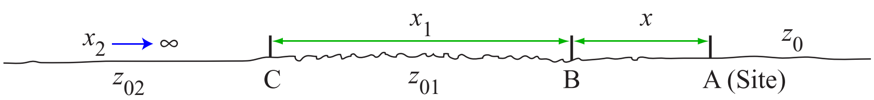
P_N	probability of an extreme wind speed being equalled or exceeded once in N years	
P_{Nr}	probability of reference wind speed of return period T_r being equalled or exceeded in N years	
q	dynamic pressure, $\frac{1}{2} \rho V^2$	kN/m^2
R	roughness-change parameter; $\lvert \ln(z_0/z_{01}) \rvert / (u_*/(fz_0))^n$ where $n = 0.23$ and 0.14 for smooth-to-rougher terrain and rough-to-smoother terrain respectively	
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.e.* 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 01008[25]) 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.

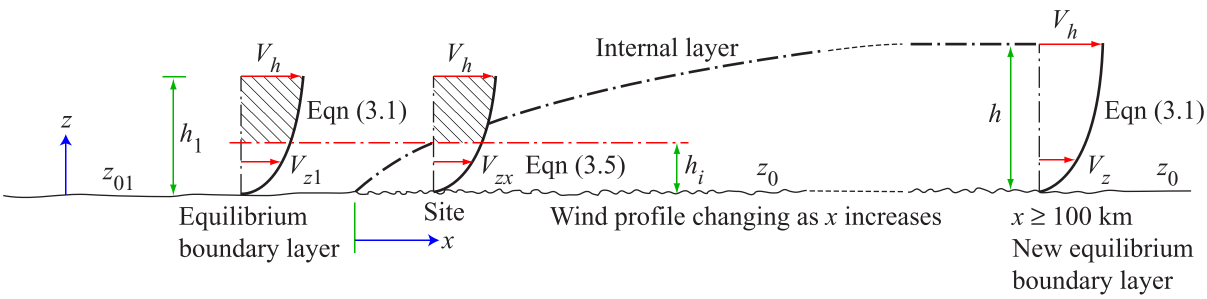
2.3.2 The time-series approach

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

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

where $$u_{*r} = V_r / K_{z*r} \tag{3.2}$$

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

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

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 $z \le h_i$; $K_x = V_{zx}/V_z$	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 ($z \le h_i$) the wind speed, V_{zx} , is dependent on x and is given by

$$V_{zx} = V_z K_x \tag{3.5}$$

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° – 250° 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 Cook[21] 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.

$\theta°$	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_{Nr} 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

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

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

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

For sites in the UK it is found[18] 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_{Nr} 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_{Nr} 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), $P_{Nr} = 0.636$ and hence $K_{Nr} = 1$. 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_{Nr} corresponding to $N_r = 50$ years and K_{Nr} 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,

$$z_0 = \frac{u_{*r}^2}{70g} \tag{6.1}$$

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

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

so that

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

which for $\lambda \geq 0.2$ reduces to

$$d = H - 4.3z_0(1-\lambda). \tag{6.4}$$

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.

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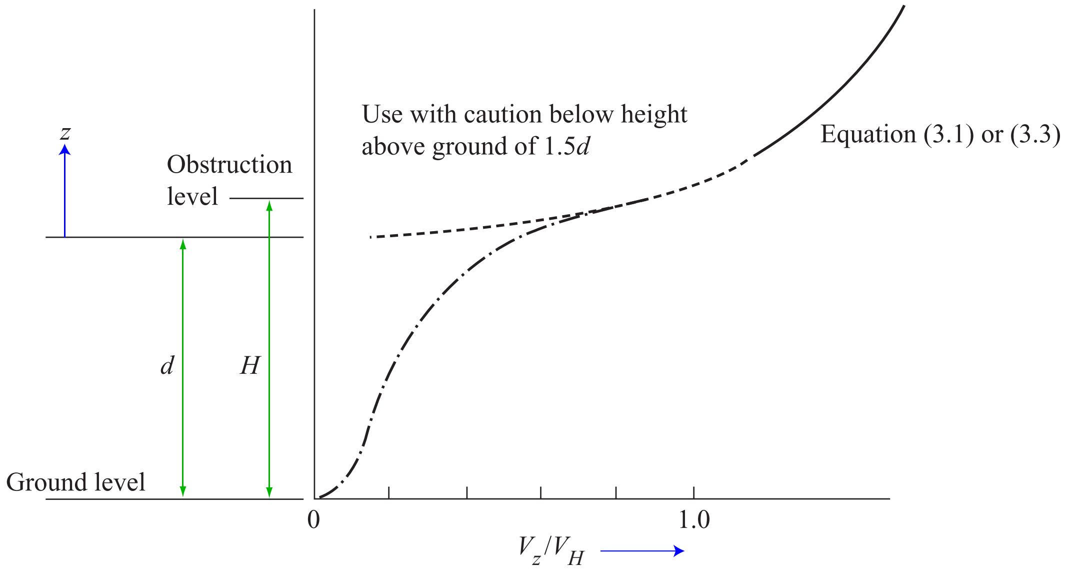
* Wave height is not only dependent on local wind speed but is affected by disturbances propagated to the site from a wide area.

Typically, in a city such that $H \approx 25$ m and $z_0 \approx 0.8$ m, $H-d \approx 2.5 z_0$ 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 1.5 d 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

$$K_{s*} = u_*/u_{*r} \tag{7.1}$$

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

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

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

$$K_s = V_{10}/V_{10,\,r} \tag{7.3}$$

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

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

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 .

9. VARIATION OF WIND SPEED DUE TO CHANGES IN UPWIND TERRAIN ROUGHNESS: The Factor K_x

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 several hundred kilometres 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 unlikely. 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.

Where terrain roughness changes are involved it is recommended that the software package (E0108), described in Section 2.2, be used. However, a simplified hand-calculation method is described in the following text (and in Sections 9.1 and 9.2) that can be used for quick estimates or check calculations.

For a single step change in roughness a new internal layer develops, as illustrated in Sketch 9.2. Within this new layer the wind speed, V_{zx}, is dependent on x and equal to $V_z K_x$. Above this layer it may be assumed that the wind speed is independent of x and equal to V_{z1}, the value (at the same height) just upwind of the step change in roughness. At intermediate heights there is a transition in wind speed between $V_z K_x$ and V_{z1}. However, for the purposes of simplified calculation, it may be assumed (as illustrated in Sketch 9.2) that the wind speed profile consists of a lower segment where wind speed, V_{zx}, is given by $V_z K_x$ and an upper segment where $V_{zx} = V_{z1}$. The two segments intersect at the height (h_{iA}) at which $V_z K_x = V_{z1}$. Within the internal layer, values of K_x are independent of z and are given by Figure 8 or Equations (A2.2) and (A2.3) in Appendix A which explains the derivation of the data. The procedure for estimating K_x, and the wind profile downwind of a roughness change, is given in Section 9.1 and is built into the calculation sheet (Table 13.2).

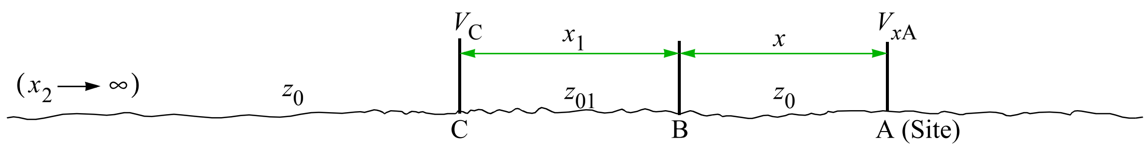
When there are several step changes in z_0 upwind of the site in question, the procedure for estimating the effect of a single step change can be adapted as described in Section 9.2.

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 estimating the effect of two step changes in z_0 (as described in Section 9.2) indicate that when the value of z_0 for the terrain roughness at the site in question and the corresponding value for the terrain upwind of the initial change are the same (as in Sketch 9.1) the following generalisation.s can be made.



Sketch 9.1 Uniform terrain (z_0) with an intermediate region of different roughness (z_{01})

(a) When $x = x_1$ the velocity profile at A (the site in question) is restored to that occurring at C just upwind of the initial step change, *i.e.* $V_{xA} = V_C$. This result applies for both smooth-rough-smooth and rough-smooth-rough terrain changes.

(b) When $x > x_1$ the same result as (a) can be assumed. The reason for this is that at the location $x = x_1$ the wind speed profile will have been restored to its original upwind equilibrium conditions (as in (a)) corresponding to a terrain roughness z_0; any further increase in fetch x (greater than x_1) will have an insignificant effect on the wind profile since it has already reached its equilibrium state with respect to the underlying terrain which in this case is also of roughness z_0.

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 $x \geq x_1$.

9.1 Single Step Change in Terrain Roughness

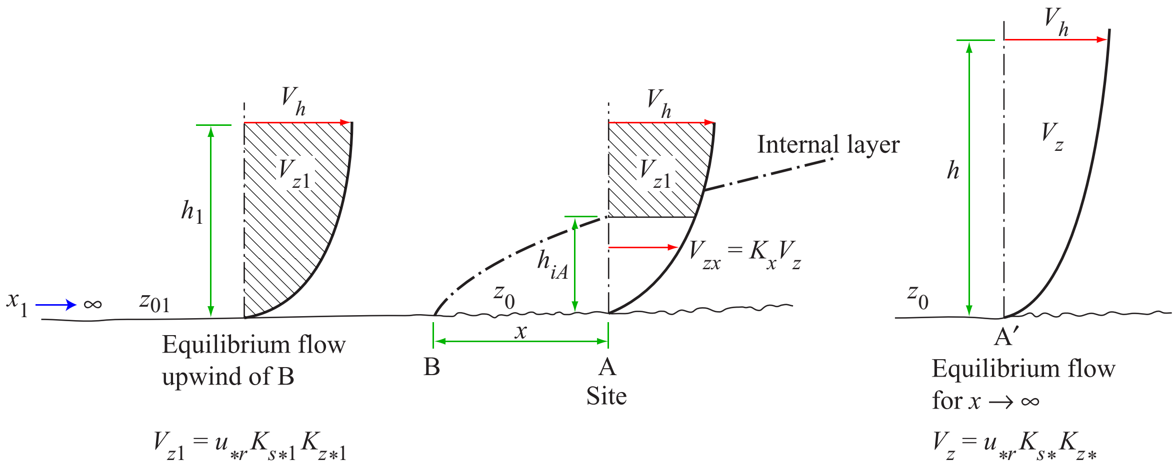
The following procedure applies for either a smooth-to-rough or rough-to-smooth change and assumes that the boundary-layer wind profile can be considered to be in equilibrium just upwind of the step change at B in Sketch 9.2 (*i.e.* the wind profile V_{z1} is not changing as x_1 increases). The procedure calculates the wind 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 9.2) for estimating the effect of more than one step change in terrain roughness on the wind speed profile. It is recommended that the Calculation Sheet (Table 13.2) 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.

(i) Estimate z_{01} for the upwind terrain and z_0 for the terrain at the site in question using Table 13.1.

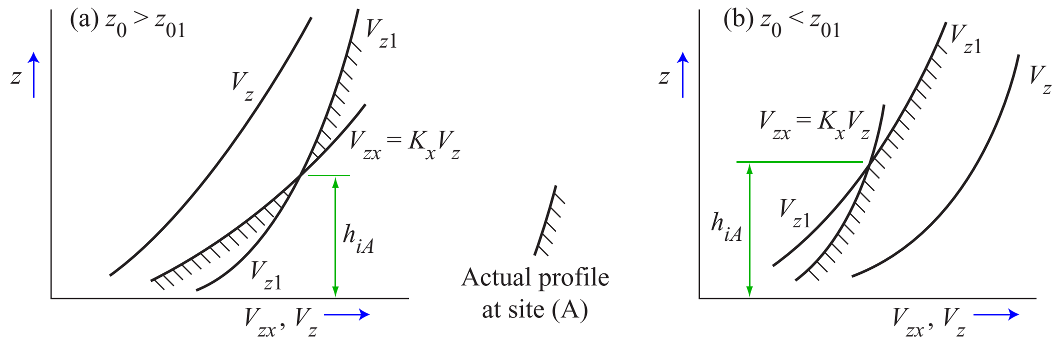
(ii) If u_{*r} is not given then calculate its value from a known reference wind speed using $u_{*r} = V_r K_{z*r}$ and hence evaluate $u_* = K_{s*} u_{*r}$ at A' (Sketch 9.2) corresponding to conditions at A when $x \rightarrow \infty$. The factor K_{z*r} is obtained from Figure 6 for z_{0r} and z_r; K_{s*} is obtained from Figure 4 appropriate to z_0 and z_{0r}. Also, evaluate $u_{*1} = K_{s*} u_{*r}$ where in this case K_{s*} is appropriate to z_{01} and z_{0r}.

(iii) Evaluate the parameter $R = \ln(z_0/z_{01})/(u_*/(fz_0))^n$ where $n = 0.23$ for a smooth-to-rough change in terrain and $n = 0.14$ for a rough-to-smooth change.

(iv) Evaluate K_x from Figure 8a for a smooth-to-rough change or Figure 8b for a rough-to-smooth change or alternatively use the corresponding equations (Equations (A2.2) and (A2.3) in Appendix A). Note that within the internal layer (Sketch 9.2) K_x does not depend on z.



Sketch 9.2 Illustration of wind profiles at the site, and upwind and far downwind of the change in roughness



Sketch 9.3 Illustration of calculation procedure

(v) For the required value of z (or specified range of values of z) evaluate V_z for the site roughness in question (z_0), assuming an equilibrium boundary layer exists there (*i.e.* $x \rightarrow \infty$), from $V_z = K_{z*} u_*$ where K_{z*} is given by Figure 6 or Equation (A1.8) in Appendix A and u_* is given by step (ii).

(vi) Repeat step (v) using z_{01} and u_{*1} to calculate V_{z1} corresponding to a location just upwind of the change in roughness at height z.

(vii) Inside the new internal layer (*i.e.* for $z \le h_{iA}$), $V_{zx} = V_z$ (step v) $\times$ K_x (step iv); above this layer $V_{zx} = V_{z1}$ (step vi) as illustrated in Sketch 9.3. The height of the interface h_{iA} can either be determined graphically from the intersection of the two velocity profiles V_{zx} and V_{z1} or it can be calculated (to a sufficiently close approximation) from

$$h_{iA} = \exp\left\{\frac{K_x(u_*/u_{*1}) \ln z_0 - \ln z_{01}}{K_x(u_*/u_{*1}) - 1}\right\} \text{ m} \tag{9.1}$$

as derived in Section A2.1 of Appendix A. This latter course is adopted in the Calculation Sheet (Table 13.2).

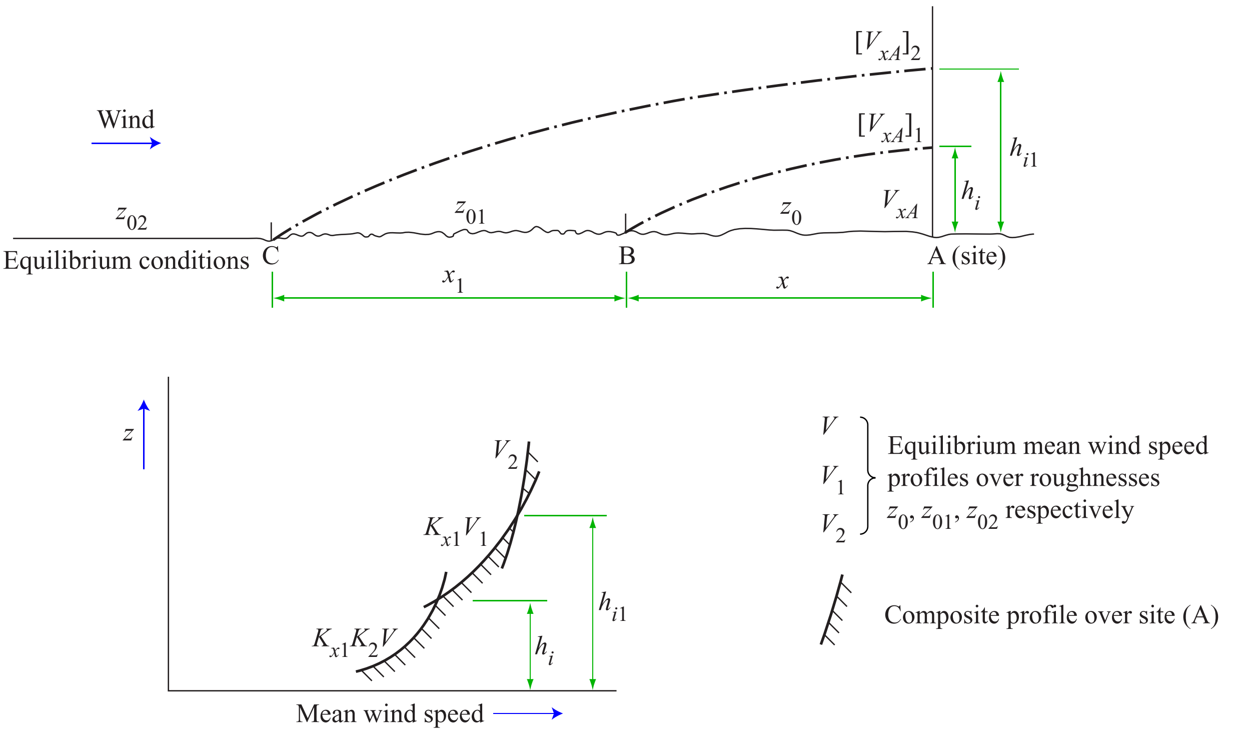
9.2 Multiple Step Changes in Terrain Roughness

For more than one change in roughness it is recommended that the program (VIEWpac E0108) referred to in Section 2.2 be used. However, the more approximate hand-calculation method described in Section 9.1 can be adapted to apply to this situation.

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, secondly, 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 provide a new internal layer at each step change which in turn influences the downwind variation of mean wind speed with height and fetch. This influence can be determined to a close approximation by adapting the method in Section 9.1 for a single step change in roughness.

The procedure for two step changes in roughness (Calculation Sheet 2 (Table 13.3)) is illustrated schematically in Sketch 9.4. It applies for two arbitrary step changes but in principle it may be extended to more. Note that if $z_0 = z_{02}$ (see Sketch 9.4) 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 9.



Sketch 9.4 Two step changes in terrain roughness

For the example shown in Sketch 9.4 with two step changes in roughness the gust profile in the height range $h_i < z < h_{i1}$ is calculated as that originating from the single roughness change at C assuming independence from the second roughness change at B. Thus,

$$[V_{xA}]_2 = V_2 = K_{x2} V_2 \quad \text{for} \quad h_{i1} < z \tag{9.2}$$

and

$$[V_{xA}]_1 = K_{x1} V_1 \quad \text{for} \quad h_i < z < h_{i1} \tag{9.3}$$

where V_1 is the mean wind speed profile that would exist in equilibrium conditions over a roughness z_{01} and K_{x1} is the value of K_x given by Figure 8 with the parameter R given by

$$R_1 = \frac{|\ln(z_{02}/z_{01})|}{[u_{*1}/(fz_{01})]^n} \tag{9.4}$$

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

In the lower inner-layer, $z < h_i$, with the assumption of equilibrium conditions at B, the wind profile over the site (A) would be given by $K_x V$ and the wind speed at $z = h_i$ would be V_1 instead of the actual value $K_{x1} V_1$. Thus the 'corrected' wind profile in the range $z < h_i$ is given by

$$[V_{xA}] = K_{x1} K_x V \tag{9.5}$$

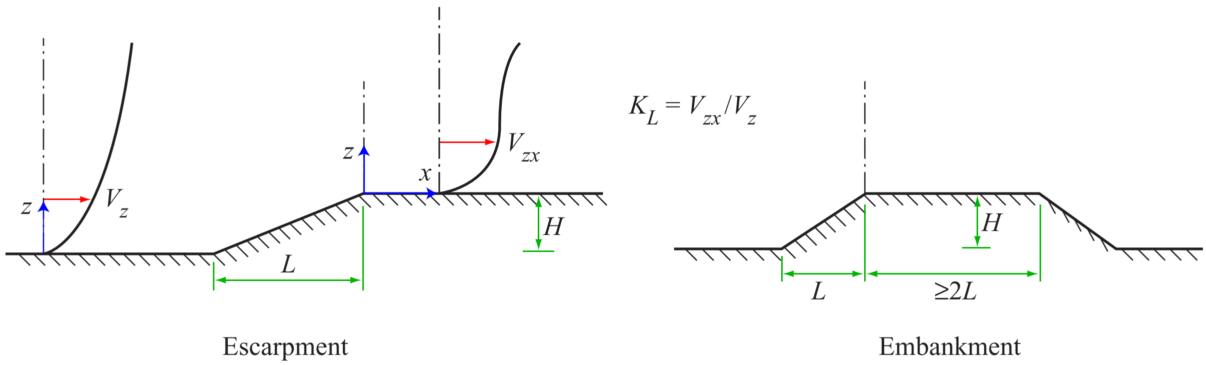
where V is the mean wind speed profile in equilibrum conditions over a roughness z_0.

The procedure can be generalised for more step changes in roughness if so required.

10. TOPOGRAPHICAL EFFECTS

Topographical effects such as those induced by local hills and valleys can affect the wind speed very significantly. This subject is now covered in ESDU 91043[24] and more comprehensively by the software described in Section 2.2. However, the data for escarpments (see Section 10.1) in Figure 9 have been retained here for interest because they represent a correlation of full-scale[19] and wind-tunnel[11] measurements for values of H/L (see Sketch 10.1) up to unity and also theoretical data[16] .

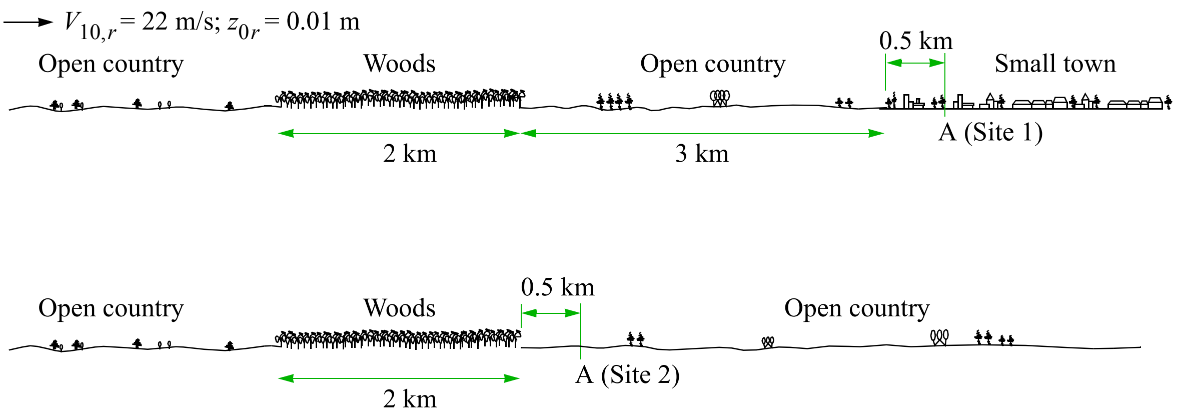
10.1 Escarpments and Embankments



Sketch 10.1

When the wind passes over an escarpment or embankment the wind speed over, and downstream of, the crest is accelerated. The ratio between this wind speed V_{zx} (at a distance x downstream of the crest (Sketch 10.1) and height z above the elevated surface) and the undisturbed wind speed V_z at the same height z measured from the upwind surface ahead of the ramp) is denoted by K_L . Values of the factor K_L given in Figure 9 for positions downwind of the crest apply both for escarpments and for embankments where the elevated plateau extends a distance of at least $2L$ (see Sketch 10.1). The data strictly only apply when the wind direction is along a line of symmetry with respect to the escarpment or embankment. Also, three-dimensional effects may be ignored providing the frontal width (normal to the wind direction) of the escarpment or embankment is greater than about $3H$.

11. EXAMPLES ILLUSTRATING THE USE OF THE DATA



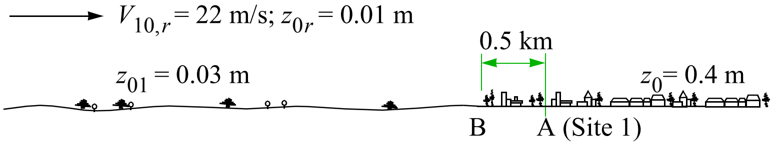
Sketch 11.1

Two nearby alternative sites are being investigated for the location of a tall mast as illustrated in Sketch 11.1. The first site is within a small town (general roof-top level about 10 m) upwind of which, in the direction of the strongest wind, is a belt of open country with a few buildings and trees with an intervening 2 km wooded region. The second site is in the belt of open country terrain but 0.5 km downwind of the wooded region. In order to assess the wind loading on the proposed mast it is required to calculate the design hourly-mean wind speed profile up to a height of 100 m at both sites that 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 the reference wind speed, $V_{10,\,r}$ (for a terrain with $z_{0r} = 0.01$ m), is assessed to be 22 m/s for both sites in the directions illustrated which represents the extreme wind for a return period of 50 years. The latitude for the sites is taken as $\phi = 52°$.

Upwind of the outer open-country regions, apart from intervening scattered villages and wooded areas, it will be assumed there are no extensive changes in terrain roughness for at least 100 km. By the criterion given in Section 9 (item (iii)), local changes in the 'open-country' wind profile, brought about when the wind passes over intervening villages or small wooded areas, are reversed once the wind has passed over the downwind open country by a distance equal to, or greater than, the span of the intervening terrain. Thus, just upwind of the wooded terrain near each site in Sketch 11.1 it may be assumed that an equilibrium boundary layer exists which can be determined directly from a knowledge of the reference wind speed.

Site 1

In this case the problem can be simplified by ignoring the intervening 2 km wooded area since downwind of this region the terrain reverts to open country for a distance (3 km) greater than the extent of the wooded terrain (see Section 9, item (iii)). With this assumption the terrain description upwind of the first site, for calculation purposes, reduces to that in Sketch 11.2 which only involves one step change in terrain roughness.

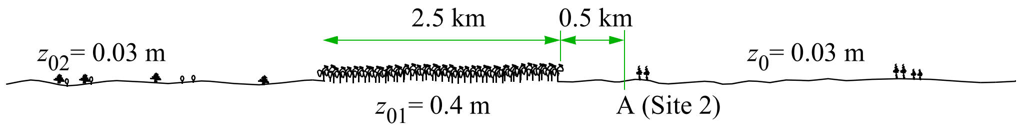


Sketch 11.2

The calculation of the wind profile at site 1 up to a height of 100 m is set out in Table 11.1 on a copy of Calculation Sheet 1.

Site 2

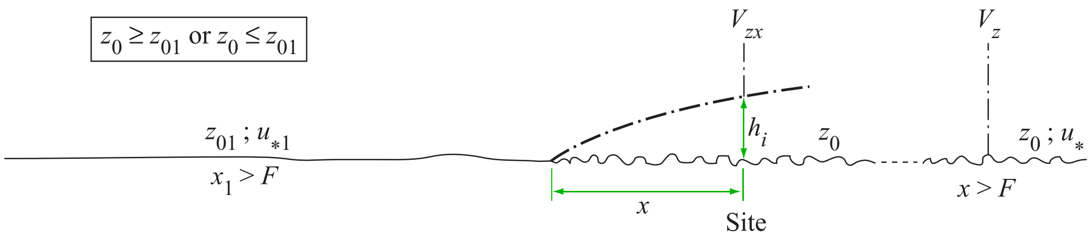
In this case no simplification of the changes in upwind terrain can be made and two step changes in surface roughness need to be taken into account as illustrated in Sketch 11.3.



Sketch 11.3

The calculation of the wind profile at site 2 up to a height of 100 m is set out in Table 11.2 on a copy of Calculation Sheet 2.

CALCULATION SHEET 1
TABLE 11.1 Calculation of Hourly-mean Wind Speed at a Site Downwind of a Sudden Change in Surface Roughness



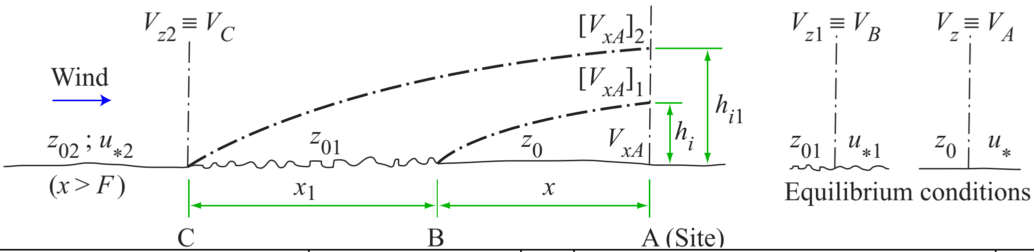
1	Site		Site 1, ϕ = 52°	15	z_0 } Sect. 6.1	m	0.4
2	Wind direction, θ (if known)		–	16	z_{01} } Table 13.1	m	0.03
3	V_r (Sect. 4)	m/s	22	17	d at site (Fig. 3)	m	10 –1.2 = 8.8
4	z_r	m	10	18	$K_{s*} = \ln(10^5/(5))/\ln(10^5/(15))$		1.297
5	z_{0r}	m	0.01	19	$K_{s*1} = \ln(10^5/(5))/\ln(10^5/(16))$		1.073
6	T_r (reference wind speed)	yrs	50	20	$u_* = (14) \times (18)$	m/s	1.908
7	$P_{Nr} = 1-(1-1/(6))^{50}$	$(N_r$=50)	0.636	21	$u_{*1} = (14) \times (19)$	m/s	1.578
8	P_N } design		0.05	22	$\lvert\ln(z_0/z_{01})\rvert = \lvert\ln[(15)/(16)]\rvert$		2.590
9	N } values	yrs	50	23*	$[u_*/(fz_0)]^n = [(20)/((12) \times (15))]^n$		11.54
10	K_{Nr} } Fig. 2 or		1.0	24	$R = (22)/(23)$		0.2244
11	K_N } Eqn (5.2)		1.155	25	x	m	500
12	$f = 1.458 \times 10^{-4} \sin\phi$	rad/s	1.15×10^{-4}	26	K_x for R and x (Fig. 8a or 8b)		1.23
13	$K_{z*r} = 2.5\ln[(4)/(5)]$		17.27	27	h_i Eqn (9.1)	m	81.5
14	$u_{*r} = [(3)/(13)][(11)/(10)]$	m/s	1.471				

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

									h_i ↓	
28	z (measured from zero plane) at site		m	5	10	20	40	60	81.5	100
29	$z + d = (28) + (17)$ = height from ground		m	13.8	18.8	28.8	48.8	68.8	90.3	108.8
30	K_{z*} for z_0, u_*, z ($\leq h_i$)	Fig. 6 or		6.320	8.099	9.844	11.72	12.84	13.72	
31	K_{z*1} for z_{01}, u_{*1}, z ($\geq h_i$)	Eqn (A1.8)							20.28	20.91
32	$V_z = (20) \times (30)$	Values for	m/s	12.06	15.45	18.78	22.36	24.50	26.18	
33	$V_{z1} = (21) \times (31)$	$x > F$	m/s						32.00	33.00
34	V_{zx} at site = (26) × (32) for $z \leq h_i$		m/s	14.8	19.0	23.1	27.5	30.1	32.2	
35	V_{zx} at site = (33) for $z > h_i$		m/s						32.00	33.0
36	K_L for topographical effects (Sect. 10)			1.0						
37	Corrected site wind speed ≈ V_{zx} × (36)		m/s	14.8	19.0	23.1	27.5	30.1	32.1	33.0

Note that $\ln \equiv \log_e$

CALCULATION SHEET 2
TABLE 11.2 Calculation of Hourly-mean Wind Speed at a Site Downwind of Two Changes in Surface Roughness



1	Site		Site 2, $\phi = 52°$	18	d at site (Fig. 3)	m	0
2	Wind direction, θ (if known)		–	19	$K_{s*} = \ln(10^5/(5))/\ln(10^5/(15))$		1.073
3	V_r (Sect. 4)	m/s	22	20	$K_{s*1} = \ln(10^5/(5))/\ln(10^5/(16))$		1.297
4	z_r	m	10	21	$K_{s*2} = \ln(10^5/(5))/\ln(10^5/(17))$		1.073
5	z_{0r}	m	0.01	22	$u_* = (14) \times (19)$	m/s	1.578
6	T_r (reference wind speed)	yrs	50	23	$u_{*1} = (14) \times (20)$	m/s	1.908
7	$P_{Nr} = 1 - (1 - 1/(6))^{50}$	$(N_r = 50)$	0.636	24	$u_{*2} = (14) \times (21)$	m/s	1.578
8	P_N } design		0.05	25	$\lvert\ln(z_{01}/z_{02})\rvert$		2.590
9	N } values	yrs	50	26	$\lvert\ln(z_0/z_{01})\rvert$		2.590
10	K_{Nr} } Fig. 2		1.0	27*	$[u_{*1}/(fz_{01})]^n = [(23)/((12) \times (16))]^n$		11.54
11	K_N } or Eqn. (5.2)		1.155	28†	$[u_*/(fz_0)]^n = [(22)/(12) \times (15)]^n$		6.201
12	$f = 1.458 \times 10^{-4} \sin\phi$	rad/s	1.15×10^{-4}	29	$R_1 = (25)/(27)$		0.224
13	$K_{z*r} = 2.5 \ln[(4)/(5)]$		17.27	30	$R = (26)/(28)$		0.418
14	$u_{*r} = [(3)/(13)][(11)/(10)]$	m/s	1.471	31	x_1	m	2500
15	z_0 }	m	0.03	32	x	m	500
16	z_{01} } Sect. 6.1, Table 13.1	m	0.4	33	K_{x1} for $R_1, x_1 + x$ (Fig. 8*)		1.14
17	z_{02} }	m	0.03	34	K_x for R, x (Fig. 8†)		0.81

* For $z_{01} > z_{02}$, $n = 0.23$, use Fig. 8a to obtain K_{x1}; for $z_{01} < z_{02}$, $n = 0.14$, use Fig. 8b to obtain K_{x1}.

† For $z_0 > z_{01}$, $n = 0.23$, use Fig. 8a for K_x; for $z_0 < z_{01}$, $n = 0.14$, use Fig. 8b for K_x.

35	z (measured from zero plane) at site	m	5	10	20	40	60	80	100
36	Height from ground = (35) + (18)	m	5	10	20	40	60	80	100
37	K_{z*} for z_0, u_*, z	Fig. 6	12.82	14.59	16.38	18.24	19.38	20.22	
38	K_{z*1} for z_{01}, u_{*1}, z	or					12.84	13.66	14.32
39	K_{z*2} for z_{02}, u_{*2}, z	Eqn (A1.8)						20.22	20.91
40	$V_z = V_A = (22) \times (37)$	m/s	20.23	23.02	25.85	28.78	30.58	31.91	
41	$V_{z1} = V_B = (23) \times (38)$	m/s					24.50	26.06	27.32
42	$V_{z2} = V_C = (24) \times (39)$	m/s						31.91	33.00
43	$V_{xA} = (33) \times (34) \times (40)$	m/s	18.7	21.3	23.9	26.6	28.2	29.5	
44	$[V_{xA}]_1 = (33) \times (41)$	m/s					27.9	29.7	31.1
45	$[V_{xA}]_2 = (42)$	m/s						31.9	33.0
46	$h_i = z$ at which (43) = (44)	m	≈80						
47	$h_{i1} = z$ at which (44) = (45)	m	>100						
48	V_{zx} at site. For $z \le h_i$, $V = (43)$. For $h_i \le z \le h_{i1}$, $V = (44)$. For $z \ge h_{i1}$, $V = (45)$.								
49	V_{zx} at site	m/s	18.7	21.3	23.9	26.6	28.2	29.7	31.1
50	K_L for topographical effect (Sect. 10)		1.0	1.0	1.0	1.0	1.0	1.0	1.0
51	Corrected site wind speed ≈ $V_{zx} \times (50)$	m/s	18.7	21.3	23.9	26.6	28.2	29.7	31.1

12. REFERENCES AND DERIVATION

12.1 References

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

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2.	ESDU	Calculation methods for along-wind loading. Part 2. Response of line-like structures to atmospheric turbulence. Item No. 87035, ESDU International, London, 1987.
3.	COOK, N.J. MAYNE, J.R.	A novel working approach to the assessment of wind loads for equivalent static design. *J. Indust. Aerodyn.*, Vol. 2, pp.149–161, 1979.
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5.	ESDU	Strong winds in the atmospheric boundary layer. Part 2: discrete gust speeds. Item No. 83045, ESDU International, London, 1983.

12.2 Derivation

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

6.	CHARNOCK, H.	Wind stress on a water surface. *Q. J. Roy. Met. Soc.*, Vol. 81, pp.639–640, 1955.
7.	COUNIHAN, J.	Wind tunnel determination of the roughness length as a function of the fetch and the roughness density of three-dimensional roughness elements. *Atmos. Environ.*, Vol. 5, pp.637–642, August 1971.
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22. TEUNISSEN, H.W. — Structure of mean winds and turbulence in the planetary boundary layer over rural terrain. *Boundary-Layer Meteorol.*, Vol. 19, pp.187–221, 1980.

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24. ESDU — Mean wind speeds over hills and other topography. Item No. 91043, ESDU International, London, 1991.

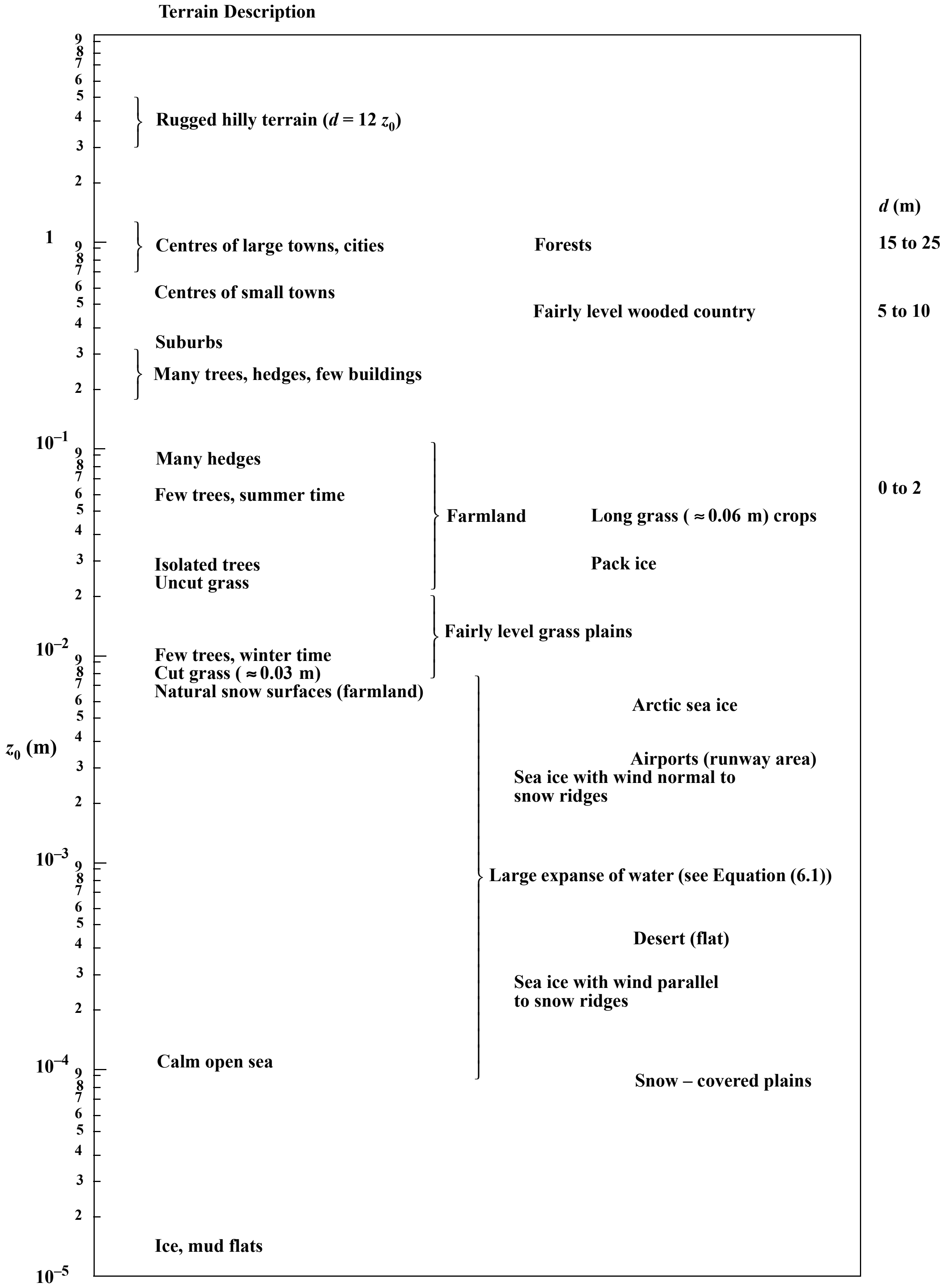
25. ESDU — Computer program for wind speeds and turbulence properties: flat or hilly sites in terrain with roughness changes. Item No. 01008 and VIEWpac program E0108, ESDU International, London, 2001. (This Item supersedes Item No. 92032.

13. TABLES FOR SURFACE ROUGHNESS PARAMETER AND CALCULATION SHEETS

Table 13.1 gives typical values of the surface roughness parameter, z_0, for various types of terrain.

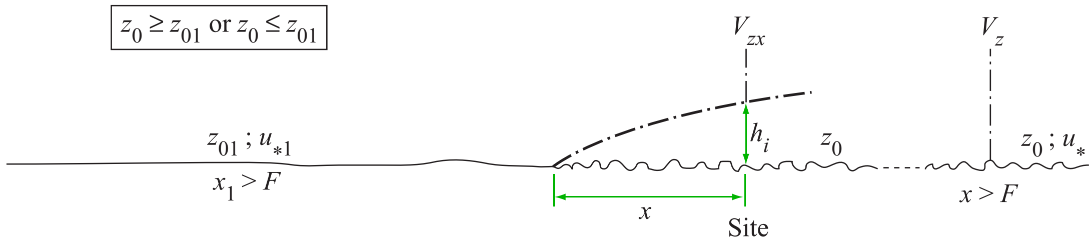
Tables 13.2 and 13.3 provide sample Calculation Sheets for applying the methods described in this Data Item.

TABLE 13.1 Values of the Surface Roughness Parameter, z_0



CALCULATION SHEET 1

TABLE 13.2 Calculation of Hourly-mean Wind speed at a Site Downwind of a Sudden Change in Surface Roughness



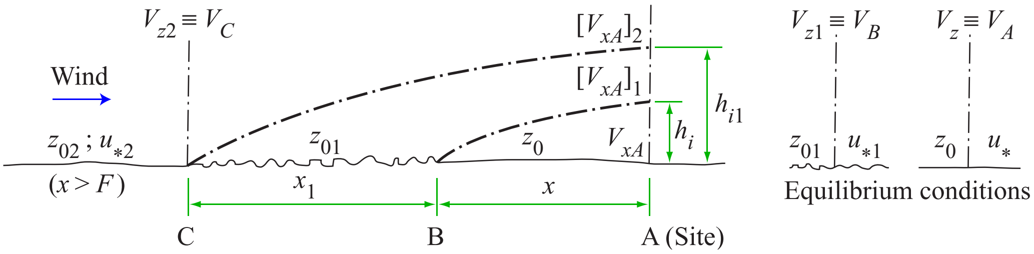
1	Site			15	z_0 — Sect. 6.1	m	
2	Wind direction, θ (if known)			16	z_{01} — Table 13.1	m	
3	V_r (Sect. 4)	m/s		17	d at site (Fig. 3)	m	
4	z_r	m		18	$K_{s*} = \ln(10^5/(5))/\ln(10^5/(15))$		
5	z_{0r}	m		19	$K_{s*1} = \ln(10^5/(5))/\ln(10^5/(16))$		
6	T_r (reference wind speed)	yrs		20	$u_* = (14) \times (18)$	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 values			22	$\lvert\ln(z_0/z_{01})\rvert = \lvert\ln[(15)/(16)]\rvert$		
9	N — design values	yrs		23*	$[u_*/(fz_0)]^n = [(20)/(12)\times(15)]^n$		
10	K_{Nr} — Fig. 2 or Eqn (5.2)			24	$R = (22)/(23)$		
11	K_N — Fig. 2 or Eqn (5.2)			25	x	m	
12	$f = 1.458 \times 10^{-4} \sin\phi$	rad/s		26	K_x for R and x (Fig. 8a or 8b)		
13	$K_{z*r} = 2.5\ln[(4)/(5)]$			27	h_i Eqn (9.1)	m	
14	$u_{*r} = [(3)/(13)][(11)/(10)]$	m/s					

* For $z_0 > z_{01}$, $n = 0.23$; for $z_0 > z_{01}$, $n = 0.14$.

28	z (measured from zero plane) at site	m								
29	$z + d = (28) + (17) =$ height from ground	m								
30	K_{z*} for z_0, u_*, $z\ (\leq h_i)$ — Fig. 6 or Eqn (A1.8).									
31	K_{z*1} for z_{01}, u_{*1}, $z\ (\geq h_i)$ — Fig. 6 or Eqn (A1.8).									
32	$V_z = (20) \times (30)$ — Values for $x > F$	m/s								
33	$V_{z1} = (21) \times (31)$ — Values for $x > F$	m/s								
34	V_{zx} at site $= (26) \times (32)$ for $z \leq h_i$	m/s								
35	V_{zx} at site $= (33)$ for $z > h_i$	m/s								
36	K_L for topographical effects (Sect. 10)									
37	Corrected site wind speed $\approx V_{zx} \times (36)$	m/s								

Note that $\ln \equiv \log_e$.

CALCULATION SHEET 2
TABLE 13.3 Calculation of Hourly-mean Wind Speed at a Site Downwind of Two Changes in Surface Roughness



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

* For $z_{01} > z_{02}$, $n = 0.23$, use Fig. 8a to obtain K_{x1} ; for $z_{01} < z_{02}$, $n = 0.14$, use Fig. 8b to obtain K_{x1} .

† For $z_0 > z_{01}$, $n = 0.23$, use Fig. 8a for K_x ; for $z_0 < z_{01}$, $n = 0.14$, use Fig. 8b for K_x .

35	z (measured from zero plane) at site		m							
36	Height from ground = (35) + (18)		m							
37	K_{z*} for z_0, u_*, z	} Fig. 6								
38	K_{z*1} for z_{01}, u_{*1}, z	} or								
39	K_{z*2} for z_{02}, u_{*2}, z	} Eqn (A1.8)								
40	$V_z = V_A = (22) \times (37)$		m/s							
41	$V_{z1} = V_B = (23) \times (38)$		m/s							
42	$V_{z2} = V_C = (24) \times (39)$		m/s							
43	$V_{xA} = (33) \times (34) \times (40)$		m/s							
44	$[V_{xA}]_1 = (33) \times (41)$		m/s							
45	$[V_{xA}]_2 = (42)$		m/s							
46	$h_i = z$ at which (43) = (44)		m							
47	$h_{i1} = z$ at which (44) = (45)		m							
48	V_{zx} at site. For $z \le h_i$, $V = (43)$. For $h_i \le z \le h_{i1}$, $V = (44)$. For $z \ge h_{i1}$, $V = (45)$.									
49	V_{zx} at site		m/s							
50	K_L for topographical effect (Sect. 10)									
51	Corrected site wind speed $\approx V_{zx} \times (50)$		m/s							

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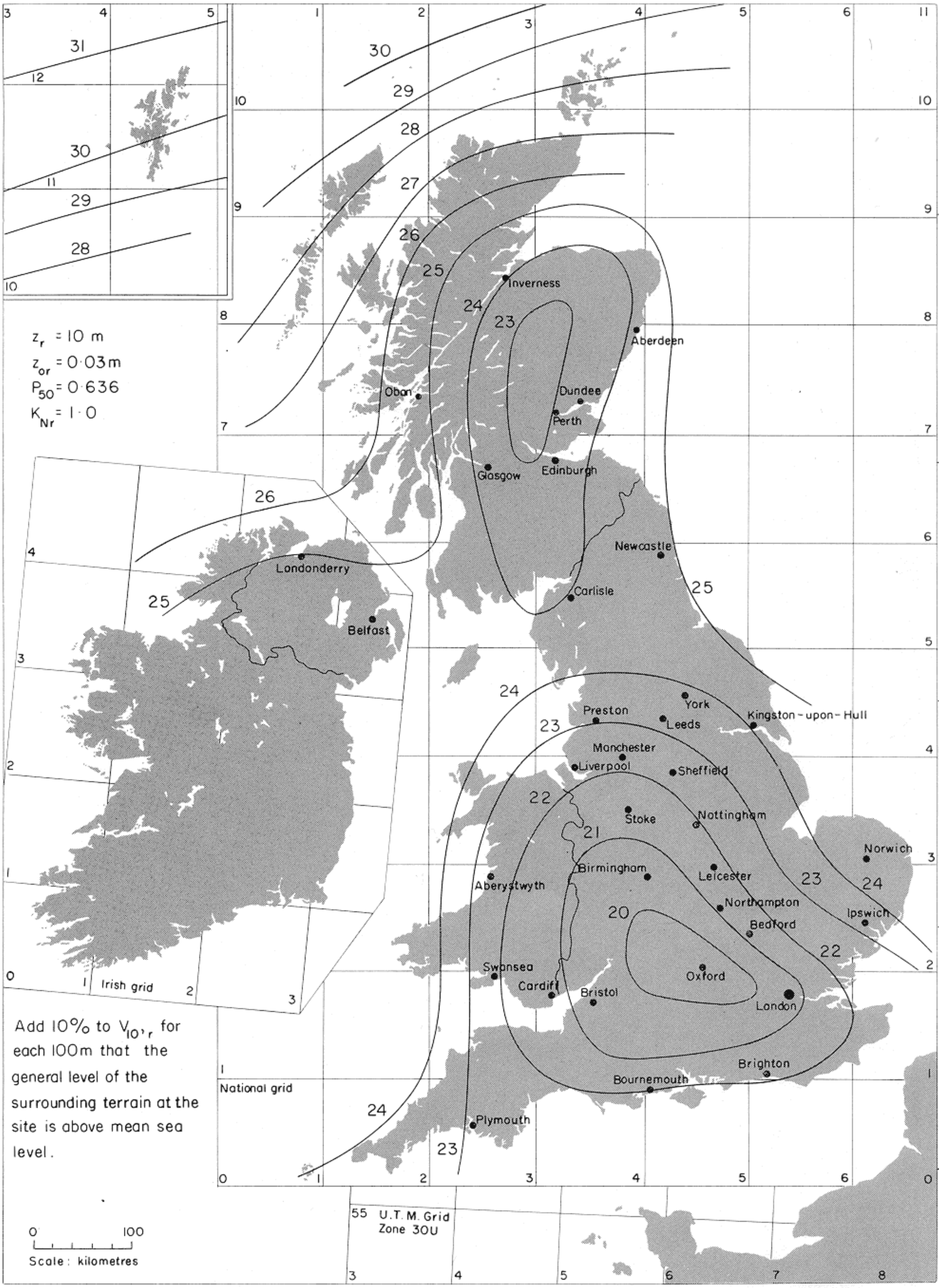

FIGURE 1a EXTREME HOURLY-MEAN WIND SPEEDS ($V_{10,r}$) IN m/s FOR THE UK WITH A 50-YEAR RETURN PERIOD ASSUMING UNIFORM OPEN COUNTRY TERRAIN

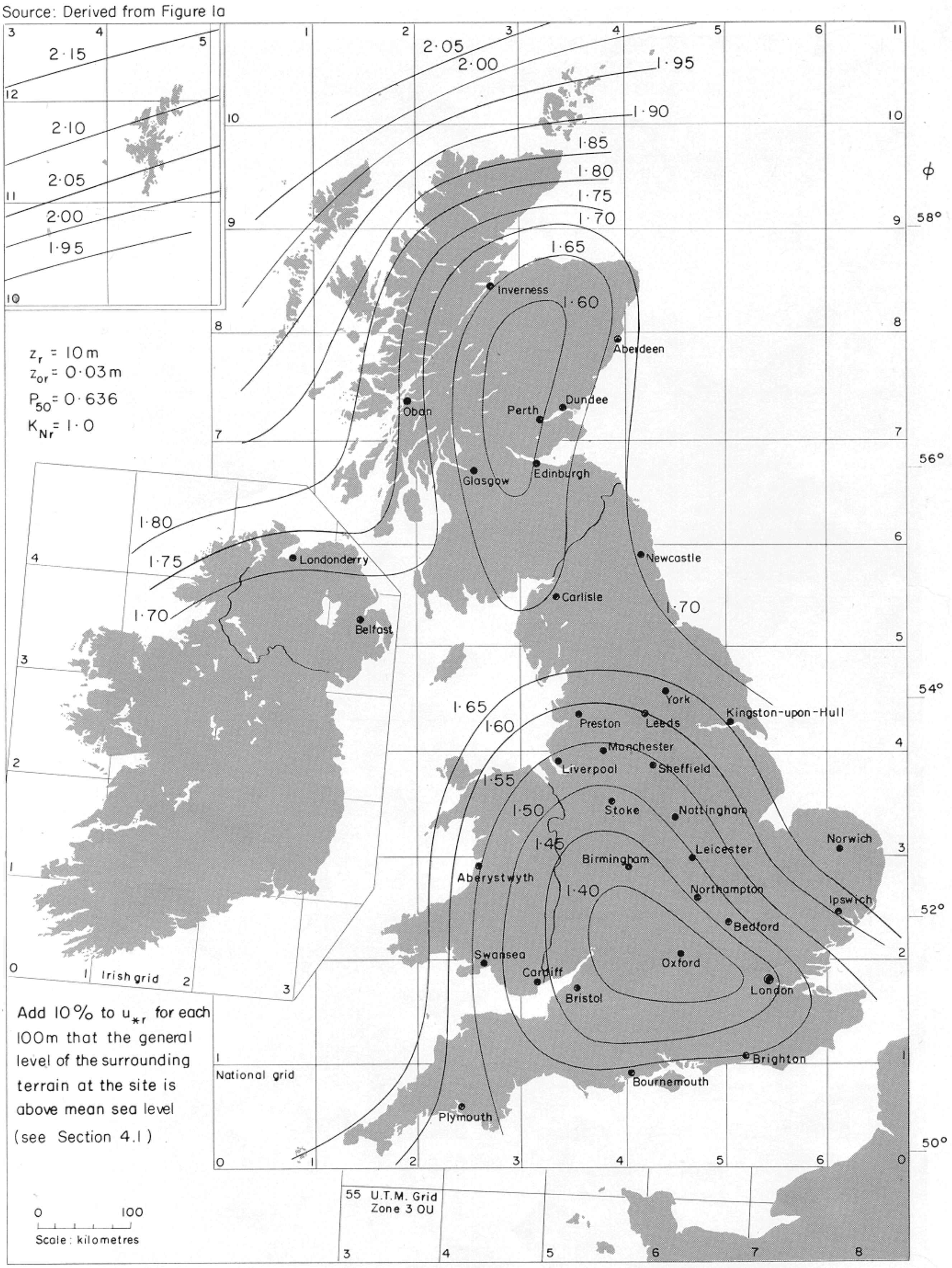

FIGURE 1b EXTREME VALUES OF FRICTION VELOCITY (u_{*r}) IN m/s FOR THE UK WITH A 50-YEAR RETURN PERIOD ASSUMING UNIFORM OPEN COUNTRY TERRAIN

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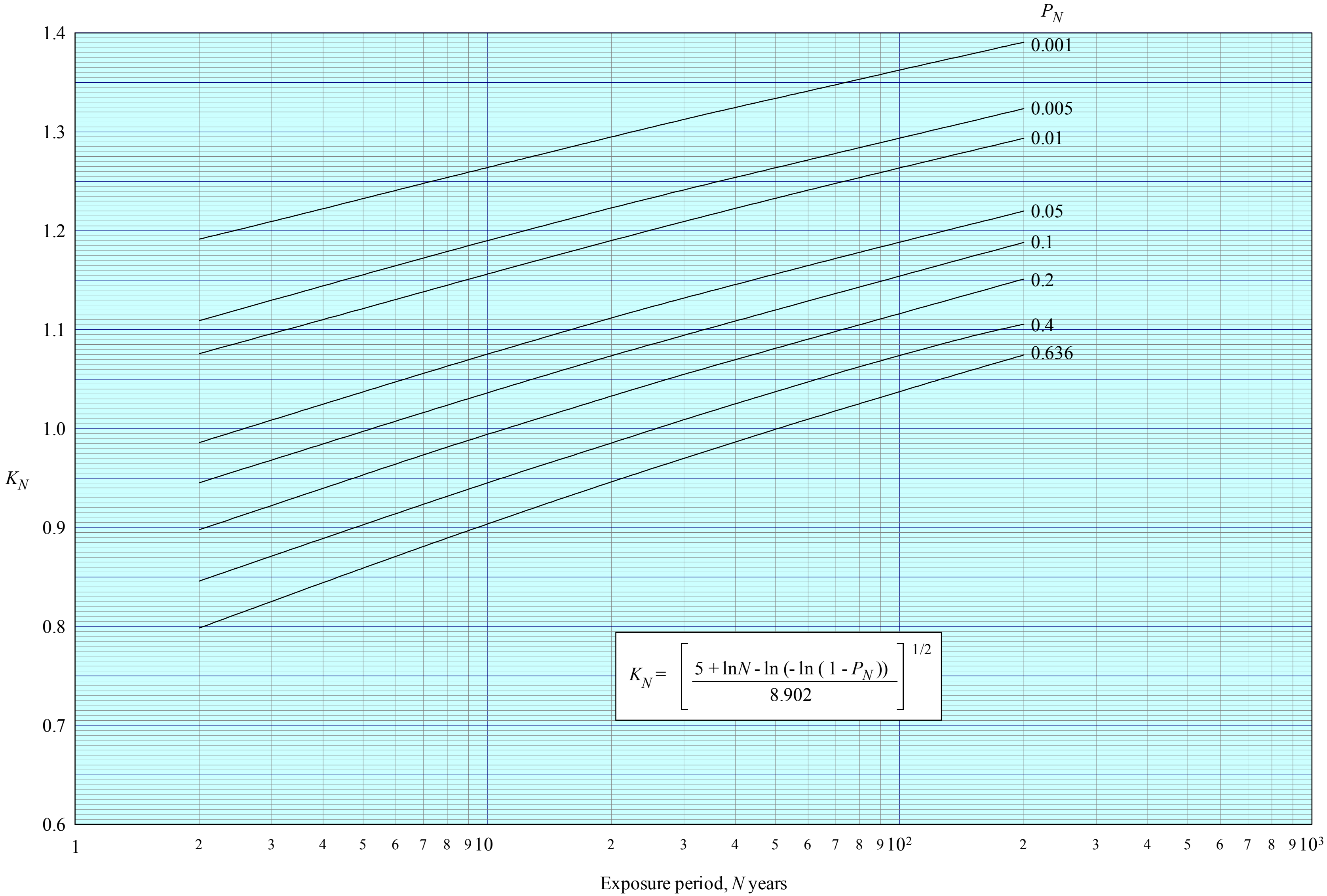

FIGURE 2 THE FACTOR K_N

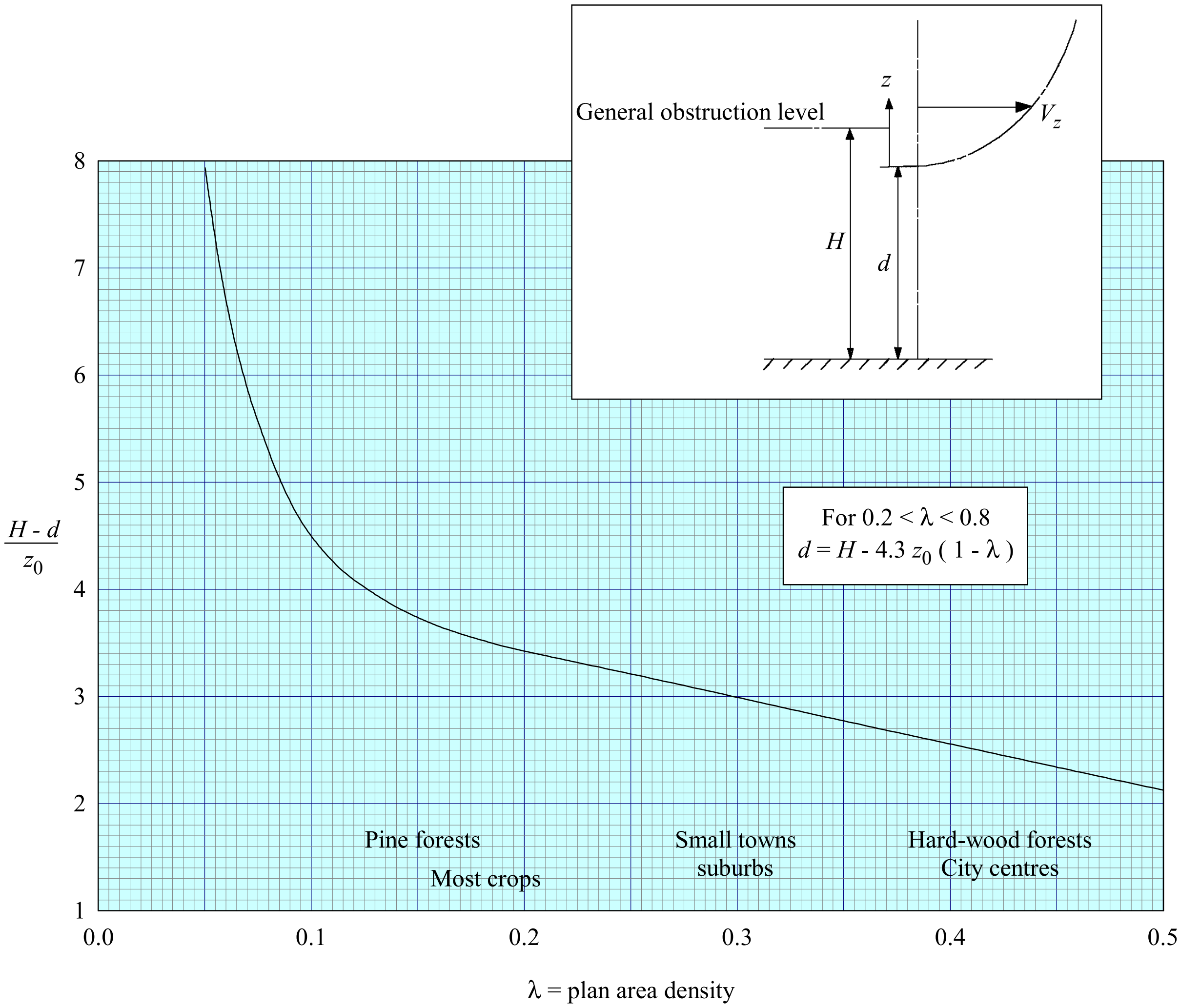

FIGURE 3 ZERO – PLANE DISPLACEMENT HEIGHT

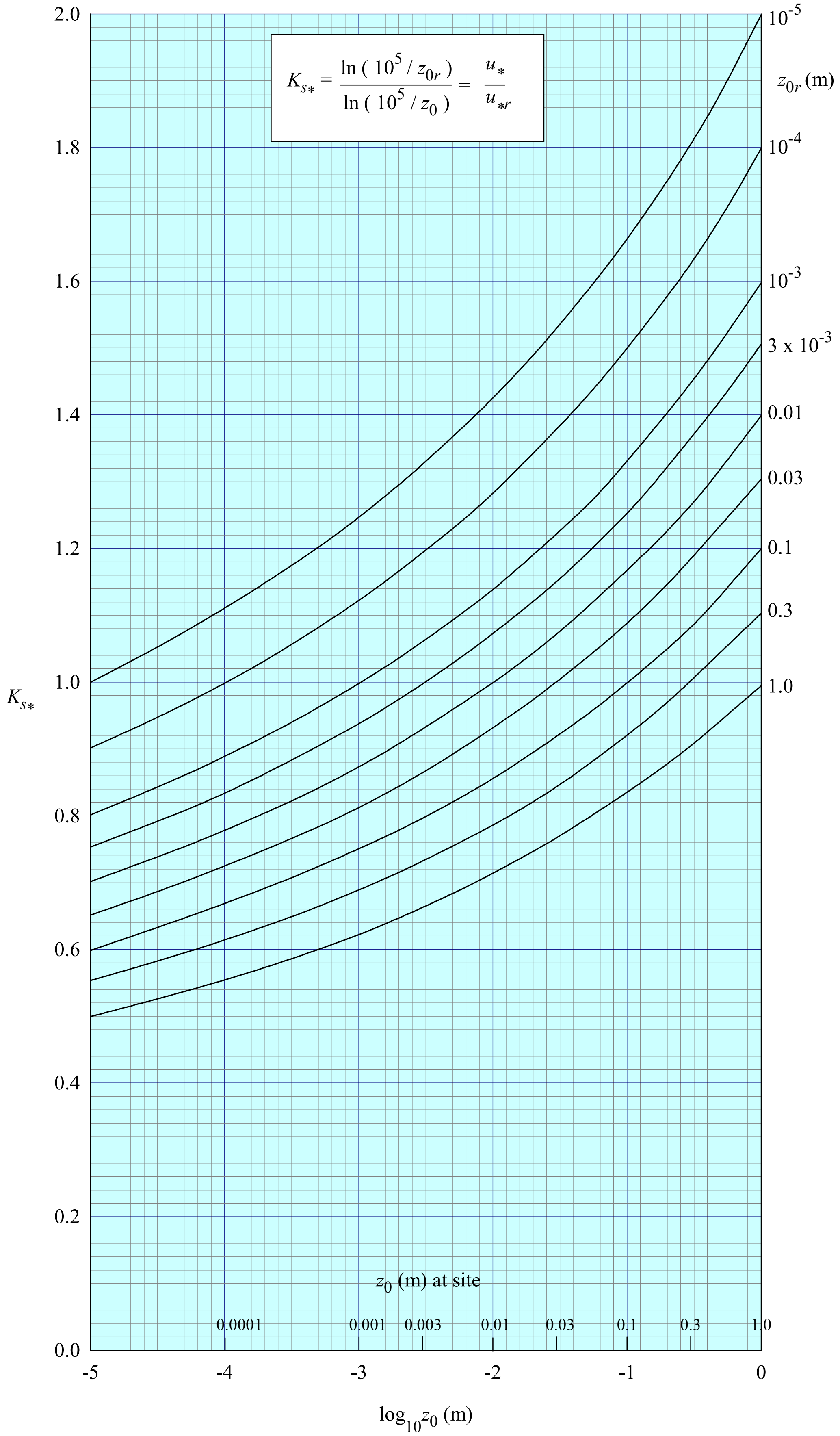

FIGURE 4 THE FACTOR K_{s*}

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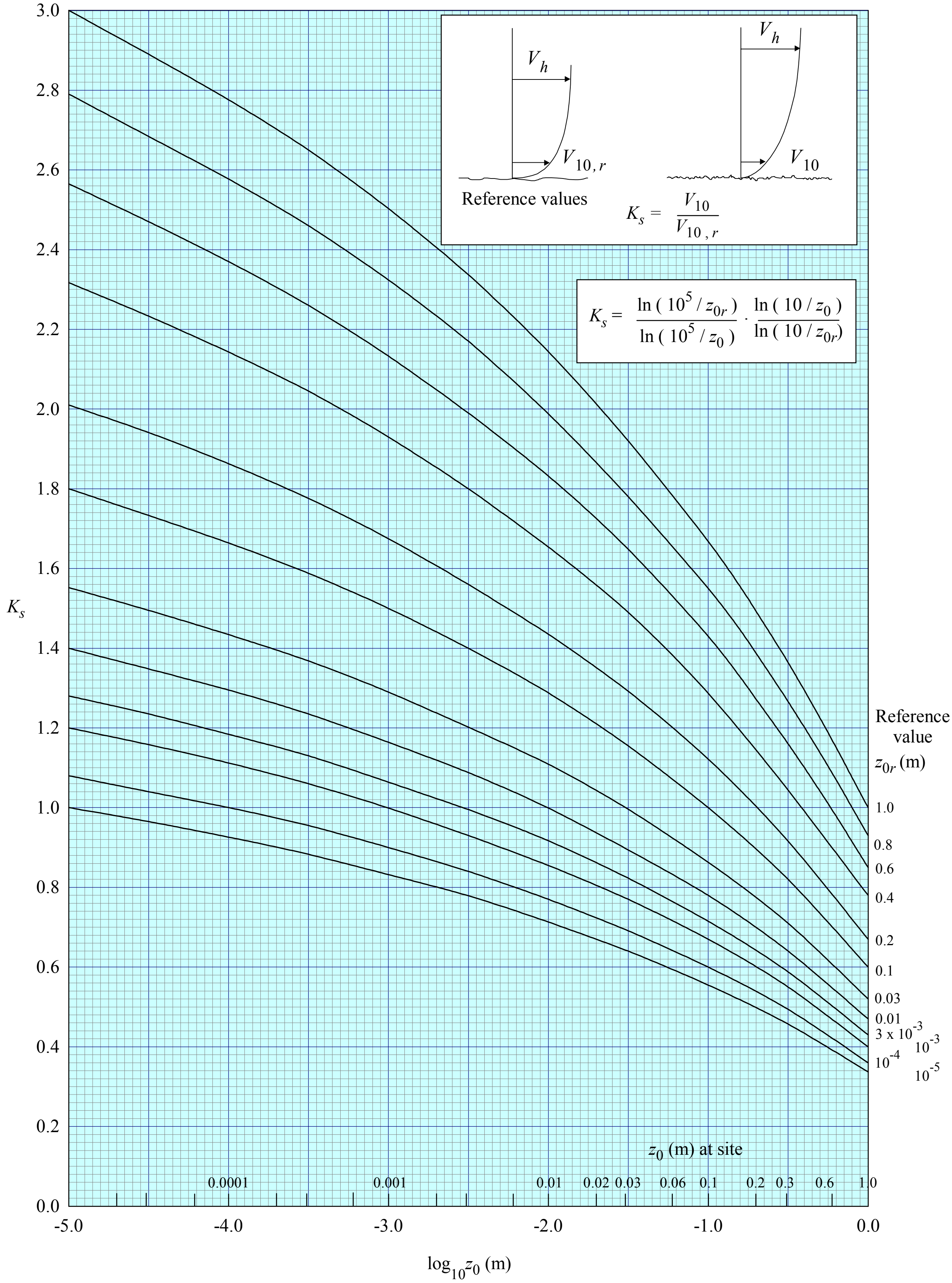

FIGURE 5 THE FACTOR K_s

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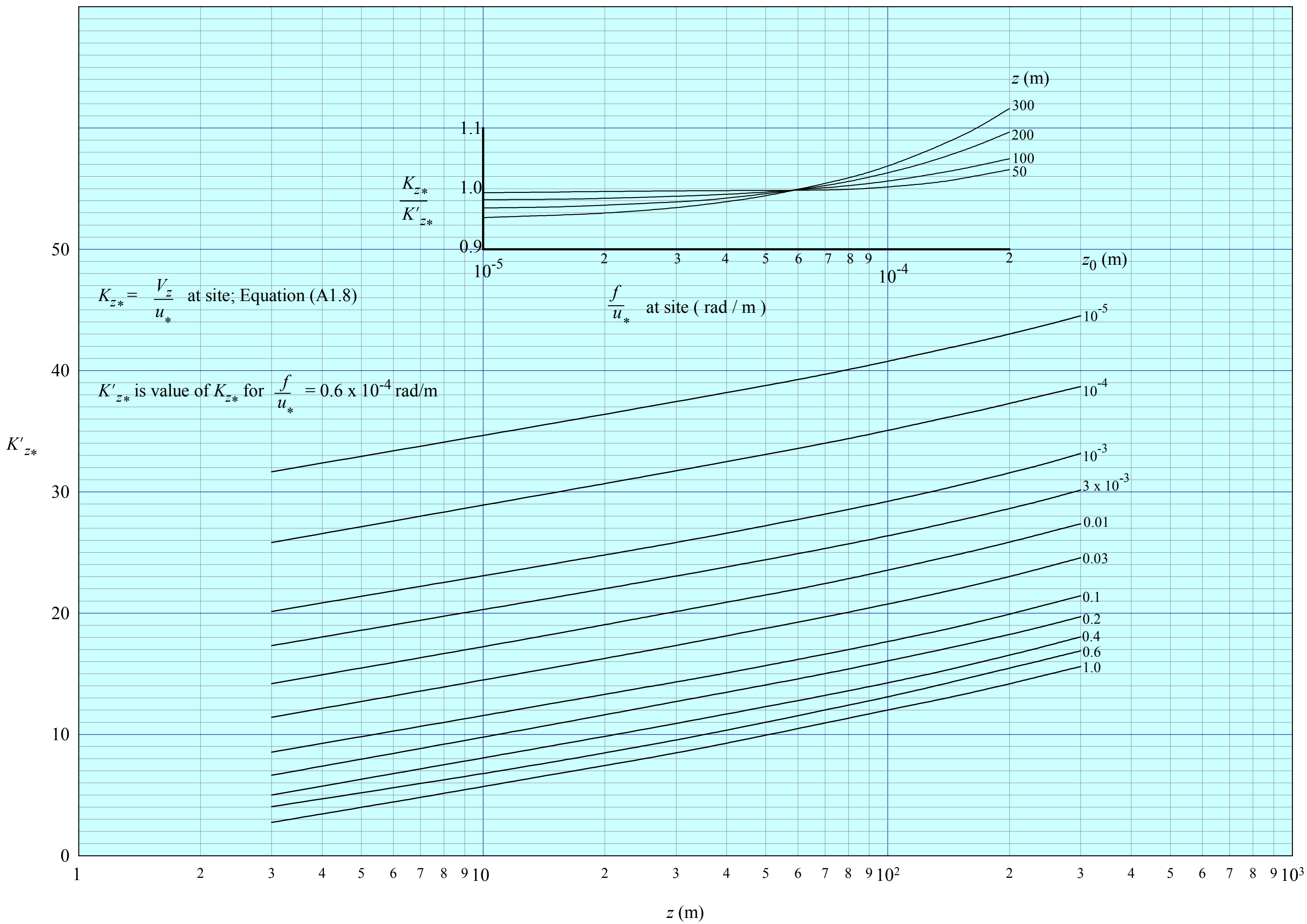


FIGURE 6 THE FACTOR $K_{z*} = \frac{V_z}{u_*}$ (Equilibrium boundary layer)

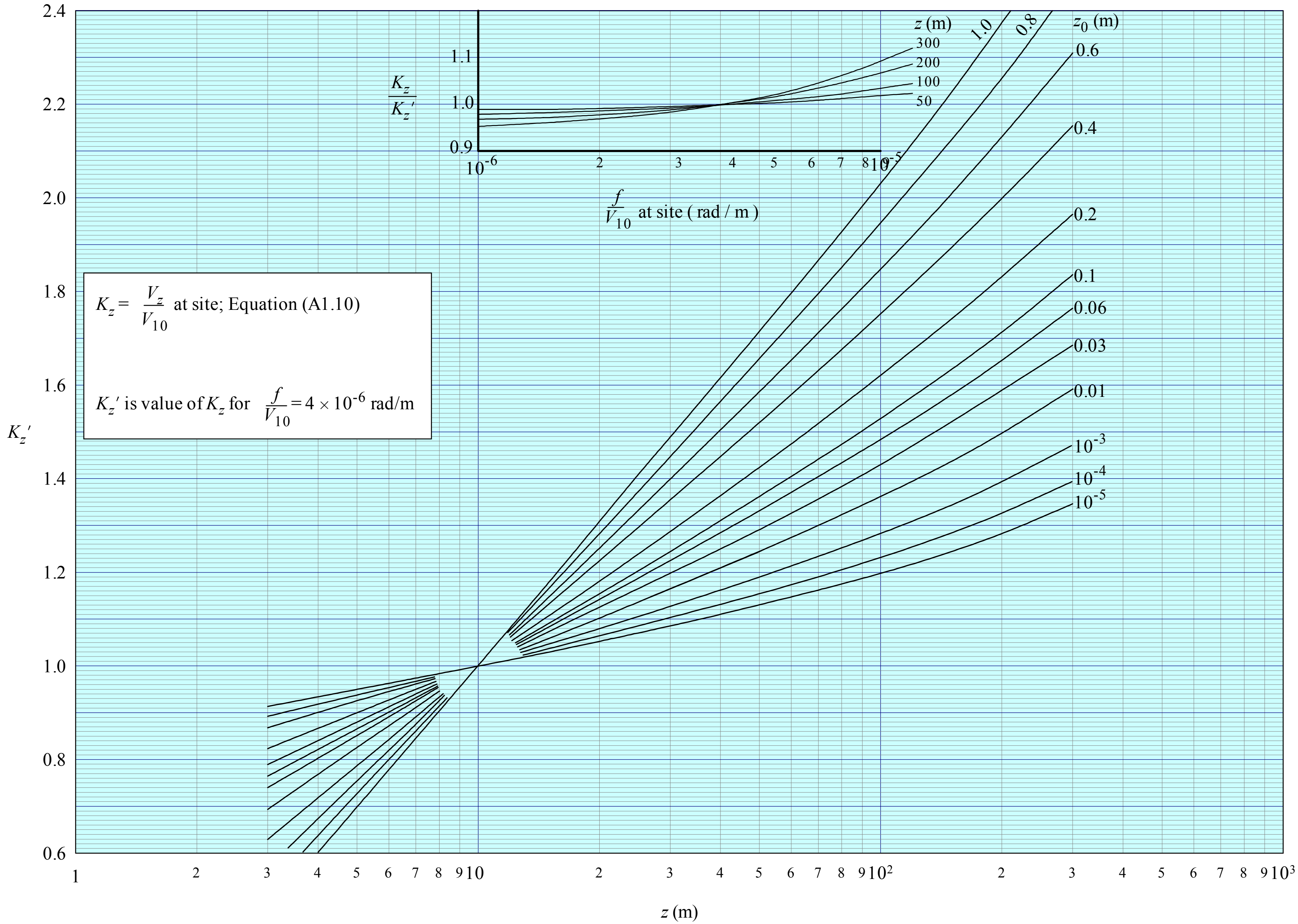
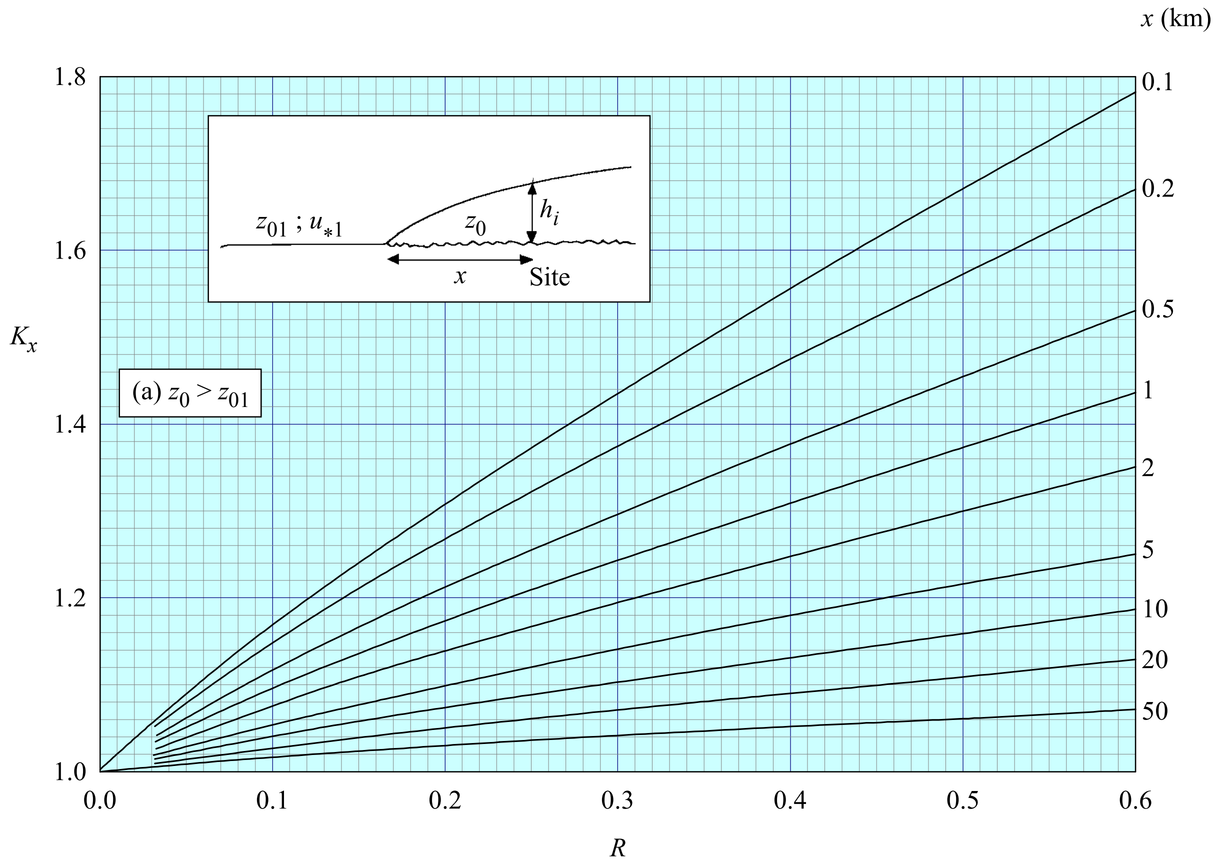


FIGURE 7 THE FACTOR $K_z = \frac{V_z}{V_{10}}$ (Equilibrium boundary layer)



$$R = \frac{\left|\ln(z_0/z_{01})\right|}{[u_*/(fz_0)]^n} \qquad \begin{array}{l} n = 0.23 \text{ for } z_0 > z_{01} \\ n = 0.14 \text{ for } z_0 < z_{01} \end{array}$$

K_x given by Equation (A2.2) or (A2.3)

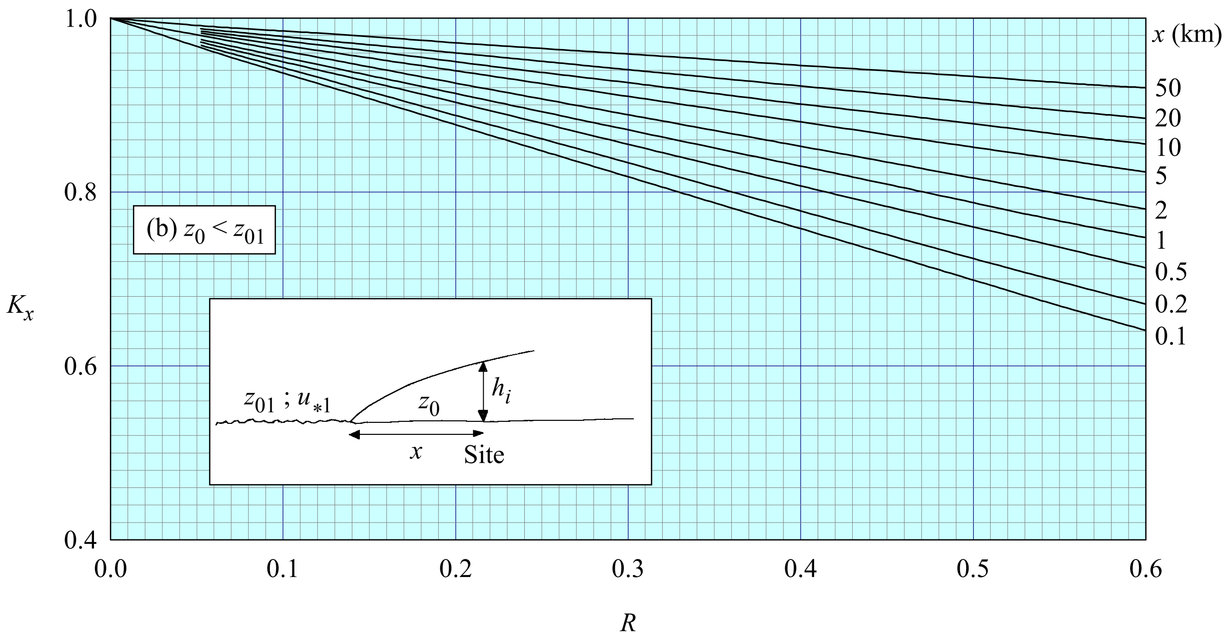


FIGURE 8 THE FACTOR K_x FOR $z \le h_i$

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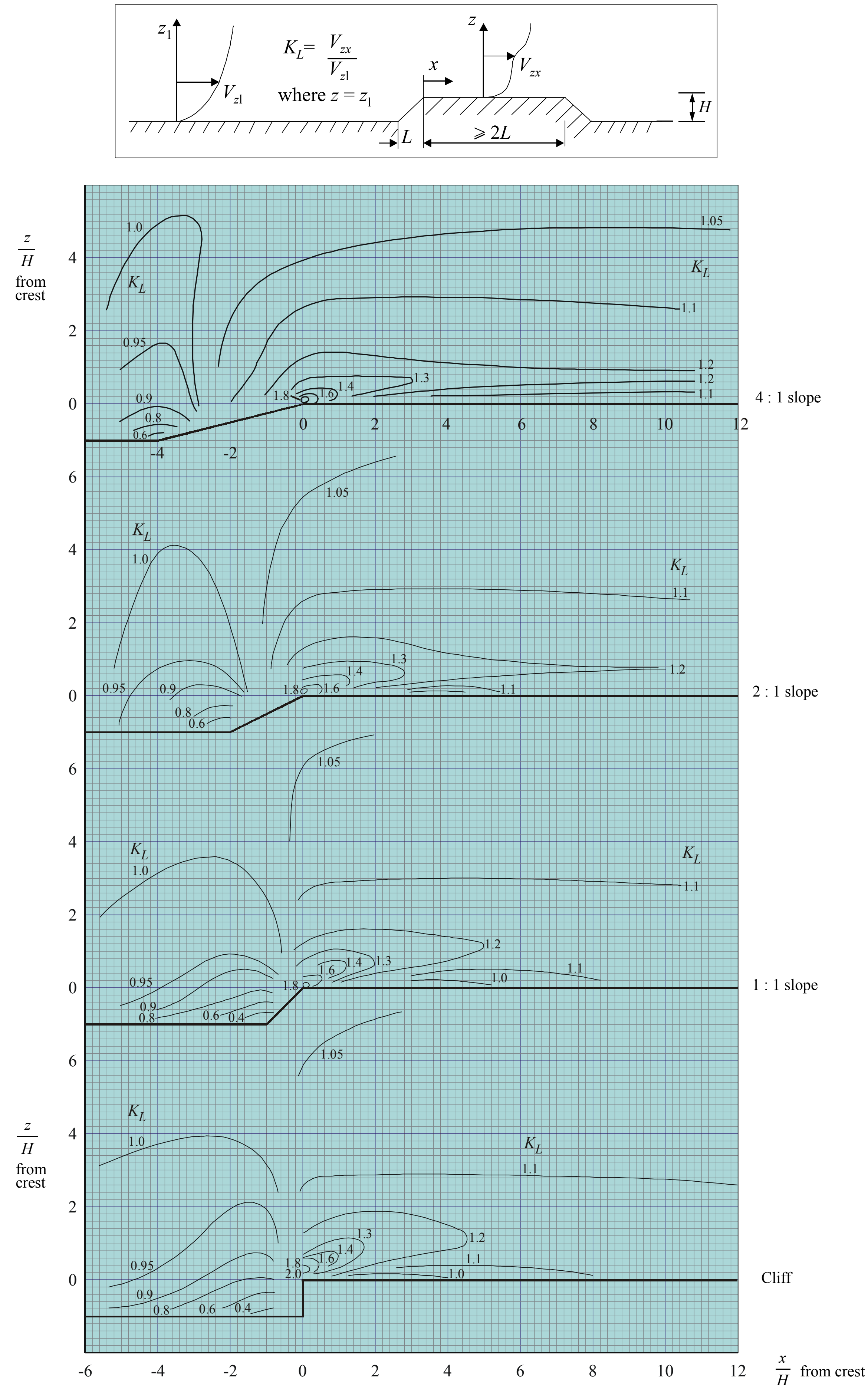


FIGURE 9 THE FACTOR K_L FOR ESCARPMENTS, EMBANKMENTS AND CLIFFS

APPENDIX A BACKGROUND INFORMATION AND DERIVATION OF THE DATA

A1. THE VARIATION OF MEAN WIND SPEED WITH HEIGHT AND SURFACE ROUGHNESS (Equilibrium boundary layer)

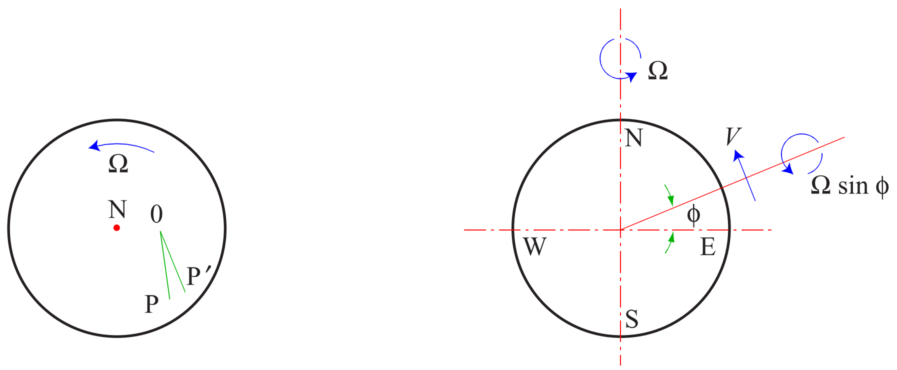
The factors controlling the horizontal mean motion of the wind are

(i) the horizontal pressure gradient,

(ii) the apparent deviating force (Coriolis force) which arises from the use of reference axes fixed on the rotating Earth (see below).

(iii) the horizontal shearing stresses associated with the interchange of momentum between the atmosphere and the surface and those associated with the vertical mixing process (Reynolds stresses) whereby the surface shear stresses are dissipated through the boundary layer by the viscosity of the air.

The Coriolis force arises in the following way. Suppose that an elemental mass of air originating at a point 0 in the northern hemisphere above the Earth's surface is directed along the path 0P fixed in space, as illustrated in Sketch A1.1. By the time the element of air has reached P the point of the Earth's surface which was originally immediately underneath P will have moved to P' due to the rotation of the Earth. Thus to an observer on the ground at P' it will appear that the element of air has been deflected to the right of its original direction. In the southern hemisphere this deflection will be to the left. When the air motion is described relative to a system of axes fixed on the rotating Earth it is thus necessary to introduce an apparent force (called the Coriolis force) into the equation of motion. The magnitude of this force per unit volume is $2\rho V\Omega\sin\phi$ where $\Omega = 72.9\times10^{-6}$ rad/s is the angular velocity of the Earth (based on a sidereal day) and ϕ is the local angle of latitude.



Sketch A1.1

Within a limited area in a weather system it is a reasonable assumption that the isobars are straight and parallel. The horizontal motion of the air relative to the surface of the Earth at the gradient height (h), where forces due to surface friction effects have become negligible, is then determined by the balance between the pressure gradient and the Coriolis force. Thus $\partial p/\partial y = \rho\, V_h\, f$ where $f = 2\Omega\,\sin\phi$. This is why closely-spaced isobars on a weather map (indicating a relatively high pressure gradient) are always associated with high wind speeds.

At ground level the horizontal shear stress (τ_0) is a maximum and equal to the drag force per unit surface area exerted on ground elements such as buildings. A parameter, u_*, defined by

$$\tau_0 = \rho \, u_*^2 \qquad \text{(A1.1)}$$

and known as the friction (or shear) velocity, is an important parameter used in scaling wind velocity through the boundary layer.

A1.1 The Factors K_{z*} and K_z

A solution of the appropriate equations of motion for a turbulent flow on the rotating Earth with a neutral atmosphere containing the factors described in Section A1 leads to a number of different laws relating the mean velocity V_z with height z and surface roughness, depending on the assumptions made. When the boundary layer is in equilibrium with the underlying surface (that is energy extracted from the flow exactly balances that associated with the generation of drag forces on elements at the surface) the vertical velocity profile does not change as the fetch (x) of approximately uniform terrain increases. In this case solutions based on so-called "asymptotic similarity theory" express the wind profile variation with height in non-dimensional form. In the lower layers of the boundary layer near the surface, wind velocity is found to be scaled to the friction velocity, u_*, and height is scaled to a roughness length z_0 related to the surface roughness, *i.e.*

$$\frac{V_z}{u_*} = \text{function of } \frac{z}{z_0}. \qquad \text{(A1.2)}$$

In the upper layers of the boundary layer the appropriate non-dimensional form is

$$\frac{V_h - V_z}{u_*} = \text{function of } \frac{z}{h}. \qquad \text{(A1.3)}$$

The equations of motion and the appropriate boundary conditions as $z \to z_0$ and $z \to h$ can be used to deduce the functional relationships of Equations (A1.2) and (A1.3). These two relationships can then be used to relate wind speed at the gradient height (h) to wind speed near the surface with the essential assumption that both equations apply in the intermediate region between the lower and upper layers of the boundary layer.

A particular solution of the full equations of motion using a modified form of the similarity theory developed by Harris[12] gives the following relationships:

$$\frac{V_z}{u_*} = 2.5\left[\ln\left(\frac{z}{z_0}\right) + a_1\frac{z}{h} + \left(1 - \frac{a_1}{2}\right)\left(\frac{z}{h}\right)^2 - \frac{4}{3}\left(\frac{z}{h}\right)^3 + \frac{1}{4}\left(\frac{z}{h}\right)^4\right] \qquad \text{(A1.4)}$$

$$\frac{V_h}{u_*} = 2.5\left[\ln\frac{u_*}{fz_0} - A\right], \qquad \text{(A1.5)}$$

and

$$h = u_*/(Bf)\,. \qquad \text{(A1.6)}$$

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The universal constants A and B were established empirically by calibrating against measured wind profile data whence $A = -1$ and $B = 6$. The constant a_1 is given by

$$a_1 = 2(\ln B - A) + 1/6 \approx 5.75 \tag{A1.7}$$

and, ignoring second-order terms, Equation (A1.4) reduces to

$$\frac{V_z}{u_*} = 2.5\left[\ln\left(\frac{z}{z_0}\right) + 34.5fz/u_*\right] = K_{z*} \tag{A1.8}$$

which can be used up to $z = 300$ m with little error compared with values given by Equation (A1.4) which applies up to $z = h$.

It follows that, to a close approximation,

$$K_z = \frac{V_z}{V_{10}} = \frac{\ln(z/z_0) + 34.5fz/u_*}{\ln(10/z_0)} \tag{A1.9}$$

which, taking $u_* = V_{10}/(2.5\ \ln(10/z_0))$, reduces to

$$K_z = \frac{\ln(z/z_0)}{\ln(10/z_0)} + \frac{86.25fz}{V_{10}}\,. \tag{A1.10}$$

A1.2 Surface Roughness Parameter z_0

For heights close to the surface (z less than about 30 m) the second- and higher-order terms of Equation (A1.4) can be neglected which then simplifies to

$$V_z = 2.5u_*\ \ln(z/z_0)\,. \tag{A1.11}$$

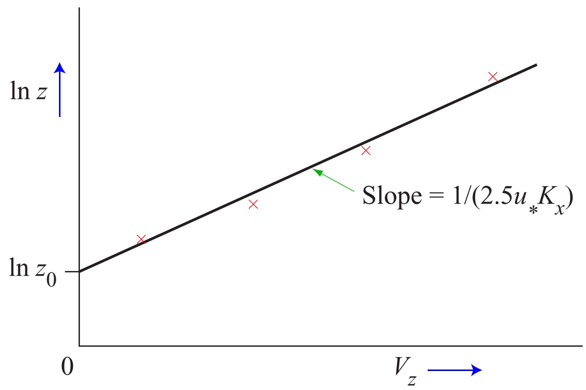
This assumes an equilibrium boundary layer but if (as derived in Section A2) the factor K_x is included to account for a change in the terrain roughness upwind of the site in question, Equation (A1.11) then becomes

$$V_z = 2.5u_*K_x\ln(z/z_0) \tag{A1.12}$$

so that

$$\ln z = \frac{1}{2.5u_*K_x}V_z + \ln z_0\,. \tag{A1.13}$$

Thus if measured values of V_z (for heights less than about 30 m) are plotted against $\ln z$ for a given site a straight line fit to the data will give a value of $\ln z_0$ as the intercept on the $\ln z$ axis as shown in Sketch A1.2.



Sketch A1.2

The values of z_0 given in Table 13.1 are based on data derived in this way.

An alternative parameter sometimes used to characterise surface roughness is the surface drag coefficient, κ_{10}, based on V_{10}. It is defined from

$$\tau_0 = \rho V_{10}^2 \kappa_{10} = \rho u_*^2 \tag{A1.14}$$

from which $\kappa_{10} = (u_*/V_{10})^2$ and, using Equation (A1.11),

$$z_0 = 10 \exp\left[-\frac{1}{2.5\,\kappa_{10}^{1/2}}\right] \text{ metres.} \tag{A1.15}$$

The particular case of the marine environment needs special consideration since the surface roughness depends on wave height which in turn is dependent to a large extent on wind strength. Charnock[6] suggests that if the surface forces exerted by the wind are dissipated in generating waves whose height is approximately proportional to z_0, then the ratio $u_*^2/(gz_0)$ will be a constant, *i.e.*,

$$z_0 = \frac{u_*^2}{cg} \tag{A1.16}$$

where g is the acceleration due to gravity and c is a constant. A collation of data from various sources[13,14], is reported in the form

$$\kappa_{10} \times 10^3 = a + b\,V_{10} \tag{A1.17}$$

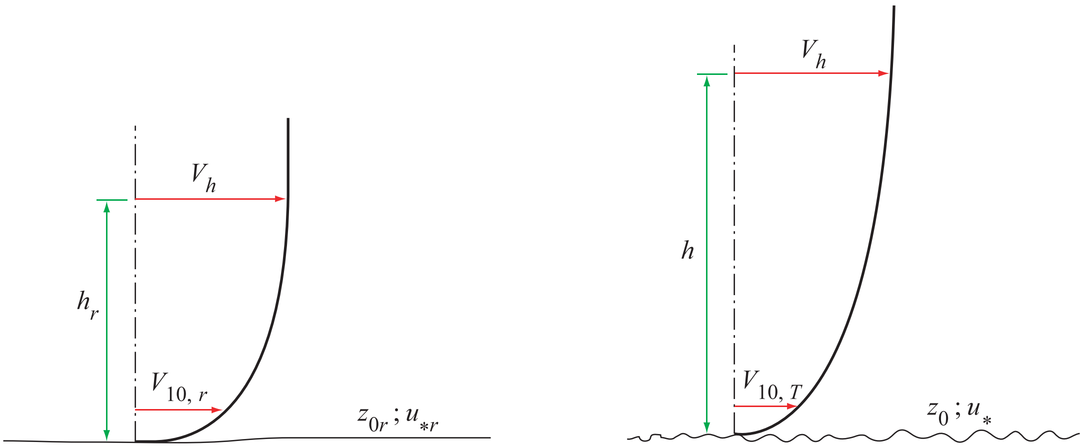
where average values of the constants are $a = 0.7$ and $b = 0.065$ s/m when V_{10} is in m/s. Equations (A1.15) and (A1.17) can then be used to evaluate z_0 in terms of V_{10} and hence in terms of u_* through Equation (A1.11) with $z = 10$ m. This variation of z_0 with u_* is then found to follow closely the form of Equation (A1.16) and a best fit to the data over a range of V_{10} from 10 m/s to 25 m/s gives $c \approx 60$. If, for convenience, a reference value of u_{*r} corresponding to $z_{0r} = 0.01$ m is used instead of u_* (corresponding to the actual sea-surface z_0) then the best fit to the data gives $c \approx 70$. Thus

$$z_0 = \frac{u_{*r}^2}{70g} \tag{A1.18}$$

where u_{*r} is a reference value ($z_0 = 0.01$ m) obtained from a source such as Figure 1b or calculated from a known reference wind speed.

A1.3 Derivation of the Factors K_{s*} and K_s

Reference wind speeds are only applicable for the type of terrain over which the measurements were made (usually open country). Adjustments to these data must therefore be made to account for any differences in terrain between the location at which the measurements were made and the site under consideration. In Equations (3.1) and (3.3) the factors $K_{s*} = u_*/u_{*r}$ and $K_s = V_{10}/V_{10,\,r}$ allow for this adjustment. They relate values of u_* and V_{10} respectively for a given terrain to corresponding values for a nearby location of different terrain using the principle that the undisturbed gradient wind speed, V_h, does not vary significantly over short distances (10–20 km). Sketch A1.3 illustrates this principle.



Sketch A1.3 Equilibrium wind profiles over different terrains with the same gradient wind speed

From Equation (A1.5),

$$K_{s*} = \frac{u_*}{u_{*r}} = \frac{\ln(u_{*r}/(fz_{0r}))+1}{\ln(u_*/(fz_0))+1}, \tag{A1.19}$$

and from Equation (A1.11), $K_s = \dfrac{V_{10}}{V_{10,\,r}} = \dfrac{u_*}{u_{*r}}\,\dfrac{\ln(10/z_0)}{\ln(10/z_{0r})}$. (A1.20)

To a close approximation (±3%) Equations (A1.19) and (A1.20) are represented by

$$K_{s*} = \frac{\ln(10^5/z_{0r})}{\ln(10^5/z_0)} \tag{A1.21}$$

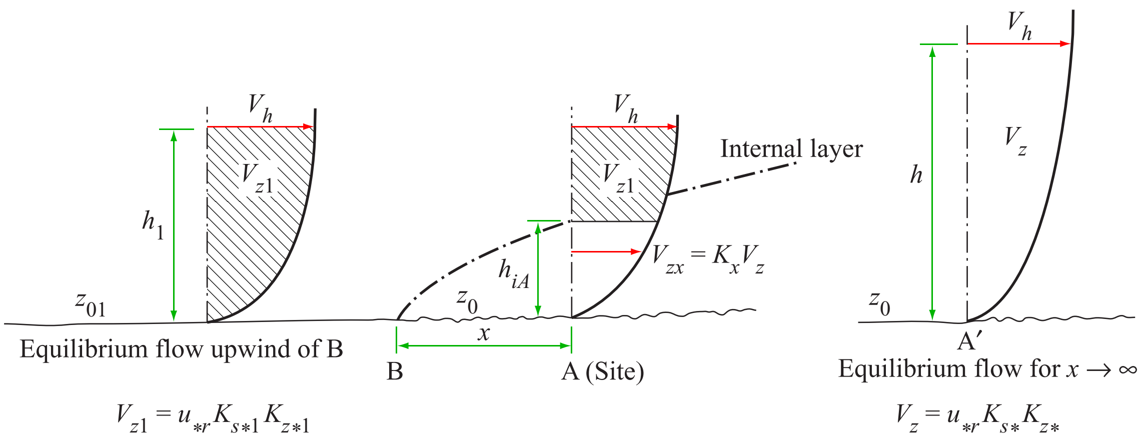
and

$$K_s = \frac{\ln(10^5/z_{0r})}{\ln(10^5/z_0)}\,\frac{\ln(10/z_0)}{\ln(10/z_{0r})}. \tag{A1.22}$$

A2. THE FACTOR K_x FOR A NON–EQUILIBRIUM BOUNDARY LAYER

A2.1 Single Step-change in Surface Roughness

A number of theoretical methods are available which deal with non-equilibrium effects due to changes in surface roughness upwind of the site in question. The results given by each of these methods, although varying in detail, are in general agreement with each other and with the limited measurements made under full-scale conditions. The method chosen in the present context is that due to Deaves[17]. It is based on a solution of the full elliptic form of the Navier-Stokes equations and, in particular, is consistent with the solution[12] for the full equilibrium boundary layer (when $x \to \infty$ or at least $x > F$) used to derive the data given in this Data Item for K_{z*}, K_z, K_{s*} and K_s. The effects of Coriolis forces are included and the solutions of the equations are obtained using a simple eddy-viscosity closure assumption and appropriate conditions on all boundaries.



Sketch A2.1 Illustration of wind profiles at the site, and upwind and far downwind of the change in roughness

Deaves has applied his method to a wide range of surface roughness changes and collapsed the data thus generated onto a series of universal curves. These curves were fitted with simple equations which can be used directly to estimate the boundary-layer velocity profile for a fetch x downwind of either a smooth-to-rough or rough-to-smooth step-change in terrain roughness. This simplified method gives results that agree, to within a few per cent, with those of the original numerical method. However, this simplified method still requires the application of seven separate equations. A further simplification has been found in the present work by correlating values of K_x (the ratio between the local wind speed at the site, calculated using the Deaves method, to that which would exist there if the upwind fetch x is greater than F) with a parameter R given by

$$R = \frac{|\ln(z_0/z_{01})|}{[u_*/(fz_0)]^n} \tag{A2.1}$$

where $n = 0.23$ and 0.14 for smooth-to-rough and rough-to-smooth changes respectively. A set of universal curves for K_x dependent only on x is then obtained which can be represented (to within about ± 3%) by the following equations:

$$K_x = 1 + 0.67\,R^{0.85} f_{sr} \quad \text{smooth-to-rough} \tag{A2.2}$$

$$K_x = 1 - 0.41\,R\,f_{rs} \quad \text{rough-to-smooth} \tag{A2.3}$$

where f_{sr} and f_{rs} are functions of x (see Equations (A2.7) and (A2.8)). To within this uncertainty, values of K_x for a given set of conditions are independent of z up to the height, h_i, at which V_{zx} first equals V_{z1} (see Sketch A2.1). Above this height it may be assumed that the velocity profile is not affected by the change in surface roughness at B (Sketch A2.1) and the wind speed is equal to V_{z1} at the corresponding value of z. In practice the transition of the wind speed profile (V_{zx}) below h_i into the wind speed profile (V_{z1}) above h_i will be more gradual; however, the departures from the above assumptions will not be greater than about ±3 % and for engineering purposes this can be ignored.

The height, h_i , of the inner layer in which K_x is a constant is given by the value of z at which $V_{zx} = V_{z1}$, or $K_x\,V_z = V_{z1}$. Taking the approximate relationship

$$V_z = 2.5 u_* \ln(z/z_0) \tag{A2.4}$$

then

$$K_x[2.5 u_* \ln(h_i/z_0)] \approx 2.5 u_{*1} \ln(h_i/z_{01}) \tag{A2.5}$$

which can be re-arranged to give

$$\ln h_i \approx \frac{K_x(u_*/u_{*1})\ln z_0 - \ln z_{01}}{K_x(u_*/u_{*1}) - 1} \tag{A2.6}$$

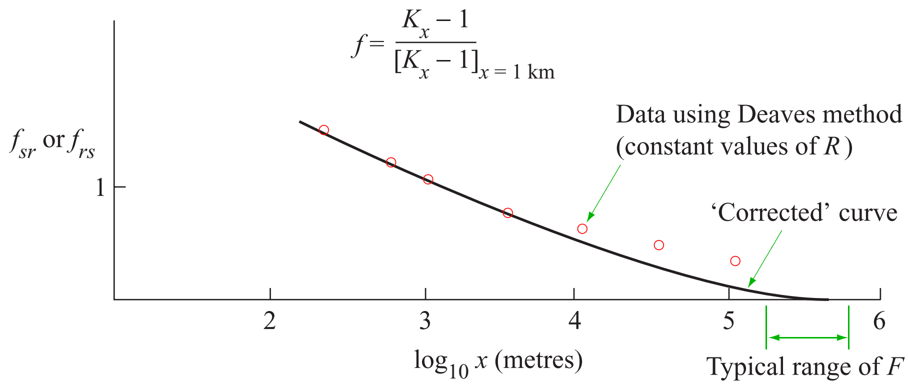
where $u_*/u_{*1} = K_{s*}$ is given by Figure 6. Equation (A2.6) only gives an approximate estimate of h_i but this is sufficient for the purpose, in the Calculation Sheets, of estimating the height range over which K_x will be approximately constant.

The particular limitations of the Deaves method are that poor accuracy is obtained for values of $x/z_0 < 10$ and for large values of x, typically when x is greater than about 3 km. However, the method does provide reasonable estimates of the fetch F required for the boundary layer to reach full equilibrium with the new surface. With this information the variation of K_x with x, for given values of R, was adjusted so that an extension of the curve through the calculated data for $x < 3$ km extrapolated smoothly to $K_x = 1$ as $x \to F$; this correction is illustrated in Sketch A2.2 and the resulting variations of f_{sr} and f_{rs} are given (in terms of $X = \log_{10} x$ metres) by

$$\left.\begin{aligned} f_{sr} &= 0.1143\,X^2 - 1.372\,X + 4.087 \ (\text{for } X \le 5.5) \\ f_{sr} &= 0 \ (\text{for } X > 5.5) \end{aligned}\right\} \tag{A2.7}$$

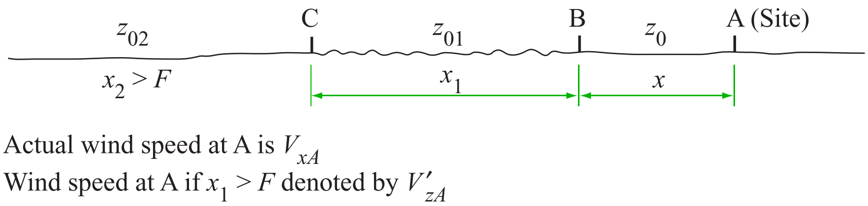
and

$$\left.\begin{aligned} f_{rs} &= 0.0192\,X^2 - 0.550\,X + 2.477 \ (\text{for } X \le 5.6) \\ f_{rs} &= 0 \ (\text{for } X > 5.6) \end{aligned}\right\} \tag{A2.8}$$



Sketch A2.2 Adjustment of the correlation of f_{sr} or f_{rs} with log x

A2.2 Multiple Roughness Changes



Sketch A2.3

The procedure for estimating the effects of more than one change in roughness, described in Section 9.2, is based on the following assumptions. Referring to Sketches 9.4 and A2.3 (which illustrates two roughness changes), in the upper layer above the site ($z > h_{i1}$) the equilibrium mean wind speed profile, V_2, originating from the roughness z_{02} will remain unaffected by the roughnesses z_{01} and z_0. The wind profile V_{x1} for $h_i < z \le h_{i1}$ will be given by the procedure for a single roughness change z_{02} to z_{01} so that $V_{x1} = K_{x1}\ V_1$ with K_{x1} determined from Figure 8 using 'x' $= x + x_1$; this again assumes that the roughness change z_{01} to z_0 will not affect conditions in the intermediate layer $h_i < z \le h_{i1}$. The internal layer height, h_{i1}, is then given by the level at which $V_{x1} = V_2$.

For the roughness change at B, if it is assumed that equilibrium conditions exist at B (*i.e.* $V_B = V_1$) then the mean wind profile, V'_x, over the site would again be given by the procedure for a single roughness change, *i.e.* $V'_x = K_x\ V$ for $z \le h_i$ instead of the actual value $K_{x1}\ V_1$. A closer approximation to the mean wind profile at the site $z \le h_i$ is, therefore, given by $K_{x1}\ K_x\ V$.

In effect an interpretation of this result is that downwind of each jth roughness change the local value of friction velocity in the innermost layer changes by an additional factor $[K_x]_{j-1}$ due to the roughness change. Thus, for j roughness changes ahead of the site, in the layer $z \le h_i$ the equilibrium values of friction velocity (u_*) and mean wind speed profile (V) that would exist at the site if $x \ge F$ are factored by $[K_x]_{j-1} \times [K_x]_{j-2} \times ...... \times K_x$ with the assumption that each roughness change can be considered independently.

A3. EXTREME VALUE ANALYSIS: The Probability Factor K_N

A3.1 All-directions Analysis

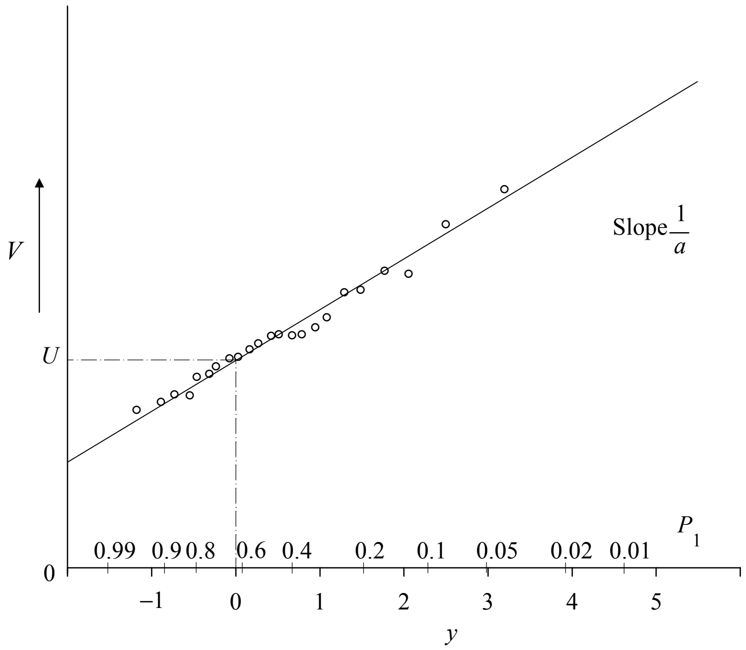
Recordings of maximum wind speed data near the ground are made at locations in many parts of the world. Provided that records have been kept over a long period of years (the more years the better) then an extreme value analysis can be applied to the data in order to determine values of maximum wind speed that have certain probabilities of being exceeded in a given number of years. For mean wind speed the distribution function of extreme values has been shown to be asymptotic to the Fisher-Tippett (Type 1) distribution as the number of independent data values increases. This distribution is given by

$$1 - P_1 = \exp[-\exp(-y)] \tag{A3.1}$$

where $P_1 = 1/T$ is the probability that an extreme wind speed will be equal to or greater than a value V in any one year*. The reduced variate, y, is given by

$$y = a(V - U) \tag{A3.2}$$

and $1/a$ and U are defined as the dispersion and mode parameters respectively which have to be determined by fitting Equation (A3.1) to measured data. The standard method for establishing this function, due originally to Gumbel[1], for annual extreme wind speeds can be summarised simply as follows.



Sketch A3.1

The annual extreme values for M consecutive years for which values of V are available are tabulated in order of increasing magnitude and an order value, m, is given to each value so that the smallest extreme value corresponds to $m = 1$ and so on. The probability, P_1, that the m^{th} value, V_m, will be equalled or

* Conversely, $1–P_1$ is the probability that an extreme wind speed will be less than, or equal to, a value V in any one year.

exceeded in any one year can be approximated by

$$1 - P_1 = \frac{m}{M+1}\,. \tag{A3.3}$$

From Equation (A3.1)

$$y = -\ln\,[-\ln\,(1 - P_1)] \tag{A3.4}$$

and if the extreme value for each year, V, is plotted against y, a linear relationship is usually obtained, as illustrated in Sketch A3.1, from which the parameters $1/a$ and U are then obtained.

If the probability of an extreme wind speed being greater than or equal to a value V in any one year is P_1 then in N years the probability, P_N, will be $1 - (1 - P_1)^N$. (Conversely, the probability of V not being exceeded in N years is $P_1{}^N$.) From Equations (A3.1) and (A3.2)

$$\begin{aligned} V &= U - \frac{1}{a}\ln\,(-\ln(1 - P_1)) \\ &= U - \frac{1}{a}\ln\,\{-\ln(1 - P_N)^{1/N}\} \\ &= U + \frac{1}{a}\,\{\ln N - \ln(-\ln(1 - P_N))\} = V\{P_N\} \end{aligned}$$

A factor K_N can be defined as the ratio of $V\,\{P_N\}$ for a given probability P_N and exposure period N years to the value for a standard condition $N = T = 50$ years which corresponds to $P_N = 0.636$. Thus

$$K_N = \frac{aU + \ln N - \ln(-\ln(1 - P_N))}{aU + \ln 50 - 0.010}\,. \tag{A3.5}$$

Because only the annual maxima of mean wind speed are used in the analysis many other relevant storm maxima are discarded in the conventional analysis. Cook[18] demonstrates how data from independent storms may be included in the analysis to provide many more data points with which to define the parameters a and U in Equation (A3.2). This leads to a greater confidence in the estimation of extreme wind speeds with a particular probability of being exceeded and permits estimation from as little as 7 years of data. The Gumbel analysis is now modified so that m_s denotes the order number within the total number of storms, n_s, and r is the average annual rate of independent storms (given by n_s divided by the record length in years). The probability, P_1, that the m_s^{th} value, V_{m_s}, will be exceeded in any one year with r **independent** storms is now given by

$$1 - P_N = \left[\frac{m_s}{n_s + 1}\right]^r \tag{A3.6}$$

and the analysis then proceeds as before.

Cook[18] further demonstrates that if the wind speed V is replaced by V^2 (or the dynamic pressure ½ ρ V^2) an even better convergence to the Fisher-Tippett (Type 1) distribution is obtained. A reduced dispersion of the data is obtained with a consequential reduction in estimated extreme values for a given return period.

The consequences of this are discussed in Section B1 of Appendix B.

Using dynamic pressure ($q = ½\rho V^2$) as the basic variable in the extreme value analysis, Equation (A3.5) becomes

$$K_N = \left\{\frac{a_q U_q + \ln N - \ln(-\ln(1 - P_N))}{a_q U_q + 3.902}\right\}^{½} \tag{A3.7}$$

where, from an analysis[20] of 50 sites in the UK, the mean value of $a_q\ U_q = 5$.

A3.2 Analysis By Direction

Cook[20, 21] has applied a similar analysis to extreme values from particular directions for 50 sites in the UK. In the first place an extreme value analysis was performed on each 30° sector independently. The ratio of the 50-year return value in each sector $(q_{50,\,\theta})$ to the corresponding all-directions value (q_{50}) can then be calculated for each sector and is denoted by c_θ. If c_θ is then used to obtain a directional design value (for a directional risk of exceedance equal to that selected for the all-directions value, P_N), then the **overall** risk of exceeding that value will be greater than that selected because of additional contributions from other directions.

Cook[21] describes a relatively simple means of transforming c_θ to obtain values C_θ $(= K_\theta^2)$ so that the **overall** risk of exceeding the directional extreme value is the same as that selected for the all-directions value. Each maximum value (q_θ) used in the original directional analysis is divided by the appropriate value of c_θ to take out the directional effect. An extreme value analysis is then performed on all these data, irrespective of direction, and a new 50-year return period value, q'_{50}, obtained which will be greater than the original all-directions extreme value, q_{50}, due to the additional contributions from each sectorial set of data. The transformed values of $C_\theta = K_\theta^2$ are then given by $(q'_{50}/q_{50})\ c_\theta$. Cook finds that for 50 sites in the UK a mean value of $\sqrt{C_\theta/c_\theta}$ is 1.11. Values of $K_\theta = C_\theta^{½}$ are presented in Table 4.1 and this factor gives directional values $V_\theta\{P_N\}$ with the same overall risk of exceedance as that selected in estimating the all-directions extreme $V\{P_N\}$.

The risk of exceeding the all-directions extreme value is not uniformly distributed by direction; there is clearly a greater risk of exceeding this value in the prevailing wind direction than in other directions. Thus, since the **overall** risk associated with K_θ is the same as that selected for the all-directions extreme, values of K_θ in the prevailing wind direction must be greater than unity.

APPENDIX B REFERENCE WIND SPEEDS

B1. REFERENCE WIND SPEEDS AND PARTIAL FACTORS

Firstly it should be understood that the current values of reference wind speed for the UK given in this Item (which are on average about 15% less than previously recommended values) are the result of an improved analysis of the basic wind data, giving more accurate and more reliable values. Thus, the probable loads experienced by structures will be more accurately represented by those calculated from this Data Item.

Secondly, it should be understood that although the inaccuracy and bias of previous data have been reduced, some uncertainty remains. A major source of this uncertainty is that due to the random nature of wind storms and as a result there is always likely to be some uncertainty remaining. This must always remain.

Thirdly, it should be noted that the standard values calculated from this Item (with $K_N = 1$), like those from the current UK Standard, are 50-year return-period values. Unfactored, this value has a very high probability of being exceeded in the period of exposure envisaged for most structures; in particular a 0.636 probability of being exceeded during any 50-year period of exposure. That is to say, it is more likely to be exceeded than not.

In actual design, loading values are usually modified in some way or other by factors designed to guard against the occurrence of larger values of load (and also against lower values of strength) than those assumed in design. However, these are not the only uncertainties involved in the erection of structures. Others are accuracy of the analytical model of the structure compared with the actual structure, quality of workmanship, durability, level of maintenance, corrosion and fatigue – and other factors which may be deliberately excluded from design considerations such as accidental loadings and design errors.

If the various partial factors which contribute to the overall safety factor were partitioned so that their role was unambiguous and specific to one and only one source of uncertainty in the design, the adjustment of that partial factor covering loading would be a relatively simple matter when new and improved loading data become available. Unfortunately this is far from being the case. There is no factor clearly applying solely to uncertainties in wind data.

For example, the values obtained from a national standard, or from any other source, are simply input to a complete design package, and resulting structures are retrospectively assessed by their subsequent performance in service. Satisfactory performance in no way confirms the accuracy of the loading assumptions; it merely confirms the validity of the complete design.

The combined effect of the design package is that generally there is a safety margin, not exactly quantifiable, which is available to cover loads greater than those assumed. The value of this margin is often sufficient to represent an equivalent reduction in the probability of exceedance to an acceptably small value such as the 5% level ($P_N = 0.05$) aimed at for other design variables. This is illustrated in Table B1.1 which shows the effect of various load factors on the probability of exceedance and the return-period of the corresponding wind speed.

TABLE B1.1 Typical Effect of Load Factor on P_N and T for $N = 50$ years

Partial Load Factor γ_f	*Equivalent Wind Speed Factor* $K_N = \sqrt{\gamma_f}$	P_N *Eqn (5.2) with* $N = 50$	T *years Eqn (5.1) with* $N = 50$
1.0	1.000	64%	50
1.1	1.049	34%	121
1.2	1.095	15%	298
1.3	1.140	6.7%	725
1.333	1.155	5.0%	976
1.4	1.183	2.8%	1767
1.5	1.225	1.2%	4310
1.6	1.265	0.48%	10530
1.7	1.304	0.20%	25640

B2. SOURCES OF DATA FOR REFERENCE WIND SPEEDS

The references (see Section B3) given in Table B2.1 will provide some data for the countries indicated but where further information is required the appropriate national meteorological office should be consulted.

The extreme wind speeds given in these references will not necessarily be hourly-mean values, nor corrected for terrain roughness changes upwind of the measuring station, or possible hill effects. In such cases the software program referred to in Section 2.2 should be applied to correct for such effects.

Additional sources for particular areas are given in Reference B12 (European regions) and in Reference B22 which provides a useful commentary on extreme wind speed data and sources for specific regions around the world (including those countries given in Table B2.1).

TABLE B2.1 Sources of Data for Reference Wind Speeds

Country	Reference	Country	Reference	Country	Reference
Argentina	B2, B6, B22	Hong Kong	B19, B22	Nigeria	B1
Australia	B11	Iceland	B15	Norway	B15
Belgium	B15	India	B9, B22	Philippines	B22
Brazil	B8, B22	Ireland	B20	Poland	B18
Canada	B16	Italy	B15	Portugal	B15
China	B14, B22	Japan	B22	South Africa	B10
Caribbean	B5, B22	Korea	B4, B22	Spain	B22
Denmark	B3, B15	Luxembourg	B15	Sweden	B15
Finland	B15	Mexico	B17, B22	Switzerland	B15
France	B15	Netherlands	B15	Thailand	B22
Germany	B15	New Zealand	B13	U.K.	B20 and Fig. 1
Greece	B15			U.S.A.	B21
				Vietnam	B22

B3. REFERENCES FOR EXTREME WIND SPEEDS

B1.	OKULAJA, F.O.	The frequency distribution of Lagos/Ikeja wind gusts. *J. App. Met.*, Vol. 7, pp. 379-385, 1968.
B2.	RIERA, J.D. REIMUNDIN, J.C.	Distribution of maximum wind velocities in Argentina. Symposium on structural loading, National University of Tucuman, Argentina. Publication IV. 3, July 1970. (In Spanish.)
B3.	JENSEN, M. FRANCK, N.	*The climate of strong winds in Denmark*. Danish Technical Press, Kobenhavn, 1970.
B4.	HUN, C.K.	Strong winds in Korea. Proc. USA – Japan Res. Seminar, National Science Foundation, Univ. Hawaii, pp. 21-25, October 1970.
B5.	SHELLARD, H.C	Extreme wind speeds in the Commonwealth Caribbean. *Met. Mag*., Vol. 100, No. 1186, pp. 143-149, May 1971.
B6.	–	Forças dedias as vento em edeficaçoes. NB 599, Associaço Brasileira de Normas Técnicas, Rio de Janeiro, 1978.
B7.	CCS	Caribbean uniform building code. Part 2. Section 2. Wind load. Caribbean Community Secretariat, Georgetown, Guyana, 1986.
B8.	NBR	Brazilian wind loading code. NBR-6123, 1987.
B9.	BIS	Indian standard for wind loads. IS 875 Part 3. Bureau of Indian Standards, New Delhi, 1987.
B10.	SABS	The general procedures and loadings to be adopted in the design of buildings. SABS 0160. South African Bureau of Standards, 1989.
B11.	SA	Minimum design loads on structures. Part 2: wind loads. Australian Standard AS1170.2-1989. Standards Australia North Sydney, 1989.
B12.	TROEN, I. PETERSEN, E.L.	European wind atlas. Published for the Commission of European Communities Directorate – General for Science, Research and Development. Risø National Laboratory, Denmark, 1989.
B13.	SANZ	Code of practice for general structural design and design loadings for building. NZS 4203, Standards Association of New Zealand, 1992.
B14.	–	Load code for the design of building structures (English translation). GBJ-9-87, Beijing. New World Press, 1994.
B15.	CEN	Eurocode 1: basis of design and actions on structures. Parts 2-4: wind actions. ENV-1991-2-4, C.E.N., Brussels, 1994.
B16.	NRC	National building code of Canada, Appendix C. NRC 1995. National Research Council, Ottawa, 1995.
B17.	LOPEZ, A. VILAR, J.I.	Basis of the Mexican wind handbook for the evaluation of the dynamic response of slender structures. Proc. 9th Int. Conf. on Wind Engineering, New Delhi, pp. 1890-1900, January 1995.
B18.	JAĞPI'NSKA, B. ZURA'NSKI, B.	Directional analysis of extreme winds in Poland. *J. Wind Engng and Indust. Aerodyn*., Vol. 65, pp. 13-20, 1996.

B19.	JEARY, A.P.	The wind climate of Hong Kong. *J. Wind Engng and Indust. Aerodyn*., Vol. 72, pp. 433-444, 1997.
B20.	BSI	Loading for buildings. Part 2. Code of practice for wind loads. BS 6399 Part 2, British Standards Institution, 1997.
B21.	ASCE	Minimum design loads for building and other structure. ANSI/ASCE 7-98. American Soc. Civil Engrs, New York, 1988.
B22.	HOLMES, J.	*Wind loading of structures*. Spon Press, London, 2001.

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