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Computer program for wind speeds and turbulence properties:

flat or hilly sites in terrain with roughness changes

Associated software: VIEWpac E0108

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THE PREPARATION OF THIS DATA ITEM

The work on this particular Data Item, which supersedes Item No. 92032, was monitored and guided by the Wind Engineering Panel. This Panel, which took over the work on wind engineering previously monitored by the Fluid Mechanics Steering Group, first met in 1979 and now has the following membership:

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COMPUTER PROGRAM FOR WIND SPEEDS AND TURBULENCE PROPERTIES: FLAT OR HILLY SITES IN TERRAIN WITH ROUGHNESS CHANGES

CONTENTS

COMPUTER PROGRAM FOR WIND SPEEDS AND TURBULENCE PROPERTIES: flat or hilly sites in terrain with roughness changes

1. NOTATION AND UNITS

		SI
d	height above ground of effective zero-plane, dependent on height and density of ground obstacles in built-up or wooded areas	m
F	value of fetch (x) for equilibrium boundary layer to have been established at site	m
f	Coriolis parameter, $f = 1.458 \times 10^{-4} \sin\Phi$	rad/s
G	distortion factor on spectral density for flow over hill; $(S_{ii})_{hill} / (S_{ii})_{flat}$, (see Section 6.7.2)	
g	gust peak factor (Section 6.2)	
H	maximum height of hill (negative if a valley)	m
h	atmospheric boundary-layer height	m
I_u, I_v, I_w	turbulence intensities of u, v, w components of turbulence respectively; $I_u = \sigma_u/V_z$, $I_v = \sigma_v/V_z$, $I_w = \sigma_w/V_z$	
K_L	speed-up factor on mean wind speed due to topography; $V_{z,\,hill}/V_{z,\,flat}$	
K_u	correction factor in evaluation of u_* (Section 6.1)	
L_{01}, L_{02}	overall length scales of topographic feature from summit to H/2 contour (see Sketch 4.4)	m
L	half width of hill at half height in wind direction	m
${}^xL_u, {}^yL_u, {}^zL_u$ ${}^xL_v, {}^yL_v, {}^zL_v$ ${}^xL_w, {}^yL_w, {}^zL_w$	integral length scales of u, v and w components of turbulence along x, y and z-axes with x-axis in wind direction and z-axis vertical	m
n	frequency	Hz
n_r	number of roughness changes upwind of site	
S_{ii}	spectral density of $i = u$, v or w components of turbulence respectively at single point in space and frequency, n	m^2/s

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t	gust duration or averaging time	s
u_*	surface friction velocity in equilibrium boundary layer	m/s
u_{*x0}	value of u_* within inner layer of boundary layer over site in non-uniform terrain	m/s
$u,\ v,\ w$	fluctuating components of wind speed along x, y and z axes respectively	m/s
V_z	hourly-mean wind speed in equilibrium boundary layer (no roughness changes upwind)	m/s
$\hat{V}_z$, V_g	gust speed averaged over t seconds	m/s
V_{ref}	reference wind speed; given wind speed (mean or gust) derived from basic wind speed maps, local met. office data or measured data at particular site, with or without terrain roughness changes upwind and/or topography effects	m/s
W_{01} , W_{02}	overall width scales of topographic feature from summit to $H/2$ contour (see Sketch 4.4)	m
$x, x_1, x_2, \ldots$	lengths of terrain associated with roughnesses z_0, z_{01}, z_{02}, …	m
x_{site}, y_{site}	co-ordinates of site in relation to $0x$, $0y$ axes of topographic feature (see Sketch 4.4)	m
z_{hill}	hill contour height measured from surrounding plateau level	m
z	height measured from ground	m
z_0	terrain roughness parameter (see Section 4.3)	m
z_{0eff}	effective value of z_0 for terrain patch (see Section 4.3.1)	
z_0, z_{01}, $z_{02}\cdots$	values of z_0 for lengths of uniform terrain upwind of site and upwind of first, second, ... step changes in z_0 respectively	m
σ_u , σ_v , σ_w	rms values of u, v, and w respectively	m/s
ψ	angle between mean wind direction and line normal to local ridge line passing through site (see Sketch 4.4)	degree
Φ	angle of latitude at site	degree

Subscripts or postscripts

flat	relates to value for flat terrain
hill	relates to value for hill (or valley)
ref	relates to values at reference site (where wind conditions are known)
site	relates to value at target site (where wind conditions are to be calculated)
x	relates to local value at site in non-equilibrium boundary layer (with roughness changes upwind)
z	relates to value at height z

2. PURPOSE AND SCOPE

For strong winds (neutral atmosphere), estimation methods are provided in ESDU 82026[6], 83045[7], 85020[12] and 86010[13] giving the variation of hourly-mean wind speed, gusts, intensities of turbulence and integral length scales and spectral densities of turbulence with height over terrain with roughness changes. For convenience, tables of wind speed factors and properties of the u-component of turbulence based on these methods are presented in ESDU 84011[9], 84030[10] and 86035[14] for various combinations of ground roughness at the site and upwind.

The computer program used to generate the data for these simple look-up tables has been extensively modified for more general use and expanded to include topographic effects. A number of features have been added to the program to assist practical application. In particular, the program has now been converted to Visual Basic and is run as a module in Microsoft Excel 97 (or later) using a spreadsheet format for entering data and printing the resultant output.

A major modification to the previous version (A9232) is that topographic effects are now computed via a program based on the theoretical model of Deaves[3] rather than on a simplified model which could only be applied conveniently to isolated hills. The program can be used to calculate wind speeds over hilly terrain which may consist of several peaks and troughs. It has also been adapted to provide estimates for steep terrain where flow separation effects occur. Also included is a simplified method for the distortion effect of topography on turbulence.

The user is recommended to use Tables 3.1 and 3.2 which provide a summary and guidance for the input data required. The rest of this document supplies more detailed information concerning the input data (cross-referenced in Tables 3.1 and 3.2), the use of the program, an example and the basis of the methods used.

The main features of the program are listed in Section 2.1 and the installation and setting up of the program is described in Section 3. A description of the input and output data formats is given in Sections 4 and 5 and a summary of the basis of the methods used is described in Section 6. Examples of the use of the program are given in Section 7 and comparisons with two sets of full-scale measurements on hills are given in Section 9.

Other programs which perform some of the same tasks as the program given in this Item have been included previously in ESDU 84011[9] and 85003[11]. These programs will give values of wind speed and turbulence intensity (I_u) to within a few percent (typically less than 5%) of the values given by the present program for a single roughness change. However, the present program has a more definitive source (see Section 6) and is likely to be more reliable in general application. It is also more comprehensive and has a research and application role in providing a means of correcting measured data to specified standard conditions.

The application of the neutral atmosphere model to tropical storms such as hurricanes and typhoons is discussed in ESDU 87034. It is reasonable to expect that over land the program can be used for such storms at heights below 200 m.

2.1 Features of the Program

The program can be used in the following ways.

(a) To calculate for a given site (and wind direction) the properties listed in (i) to (v) below for a specified reference wind speed condition (see Section 4.1.1).

(b) To investigate the effect on selected wind properties of changing some of the input variables (such as reference wind speed, ground roughness or gust averaging time). The spreadsheet presentation facilitates repeat runs with changes to the input.

(c) To reduce or correct measured wind properties (such as those from a local met. station) to values corresponding to standard conditions such as flat, uniform open country terrain, or to obtain corresponding values for some other specified terrain.

The program will calculate the following wind properties as a function of height over the site.

(i) Hourly-mean wind speed.

(ii) Maximum gust speed or 'fastest mile of wind' averaged over t seconds where $0.3 \le t \le 3600$ s.

(iii) Properties of the longitudinal (u) component of turbulence (intensity I_u and integral length scales ${}^xL_u$, ${}^yL_u$, ${}^zL_u$) and spectral density, nS_{uu}/σ_u^2.

(iv) Properties of the lateral (v) component of turbulence (intensity I_v and integral length scales ${}^xL_v$, ${}^yL_v$, ${}^zL_v$) and spectral density, nS_{vv}/σ_v^2.

(v) Properties of the vertical (w) component of turbulence (intensity I_w and integral length scales ${}^xL_w$, ${}^yL_w$, ${}^zL_w$) and spectral density, nS_{ww}/σ_w^2.

The program takes into account the following local conditions.

(1) Ground roughness at the site (z_0).

(2) Variations in ground roughness upwind of the site (z_{01}, z_{02}, *etc*., see Section 4.4).

(3) The variation of sea-surface roughness with wind speed.

(4) Height above the ground.

(5) Topographic effects on wind speed due to the location of the site in a hilly region, including ridges, embankments, escarpments or cliffs, or in a valley; also, topographic effects on turbulence properties for flow over hills with no flow separation.

(6) Variation of wind properties and turbulence with wind speed (for a neutral atmosphere).

3. INSTALLING AND RUNNING THE PROGRAM

The program E0108, which supersedes program A9232 previously available, is written in Visual Basic and runs as a module in Microsoft Excel 97 (or later). The code that runs the Excel module is hidden to ensure that only authorised changes can be made. If access is to the code is required, contact ESDU International for a password.

The input data required for the program may be considerable, particularly if the terrain is hilly. To assist in achieving a complete and correct set of input data, each Worksheet contains notes and sketches to provide guidance and copious error traps are built into the program to catch input errors. Additionally, Tables 3.1 and 3.2 provide a summary of the required input data on each Worksheet together with cross references to Sections in this Data Item where further guidance or explanation can be found.

3.1 Subscribers to Wind Engineering Series in Hard Copy (Printed Items).

The program is supplied on CD-ROM or 3½ inch disk in the Wind Engineering Software Volume. Installation instructions are provided as appropriate. The program is supplied as file* E0108V*xx*.xls, where V*xx* indicates the program version (*e.g.* V10 is version 1.0). The default installation location from the CD-ROM or from the disk is to a directory/folder C:\ESDU\Viewpacs\E0108V*xx*.

The program can be run by starting Excel and opening file E0108V*xx*.xls using File…Open, or by double-clicking the file name. The default ESDUview installation locates the file in C:\ESDU\VIEWpacs\E0108V*xx*.

It is strongly recommended that, each time the program is run, the file is saved (using File…Save As) under a new name reflecting the particular application or site location. This will ensure that the original program file is kept unchanged for future use. Input data and results from particular runs can be copied to other independent Excel Worksheets for future reference.

Alternatively, the original file can be saved as an Excel template file (E0108V*xx*.xlt) in the XLstart directory/folder (within the same directory as Excel.exe). The program can then be run by starting Excel and using File…New to select the required template. This procedure opens a separate instance of the program each time with 1, 2, 3, *etc* appended to the basic file name.

3.2 Subscribers to Wind Engineering Series on CD-ROM.

The program is also included on the Wind Engineering CD-ROM and is installed as file E0108V*xx*.xls as part of the CD-ROM installation. It may be run from ESDUscope under Programs... Wind Engineering or it can be copied from C:\ESDU\VIEWpacs\E0108 (assuming a default installation) to an appropriate location and run as described in Section 3.1.

3.3 Subscribers to Wind Engineering Series via the Web (Internet).

Subscribers who have opted for Web delivery can copy the file E0108V*xx*.xls from the ESDU web site (www.esdu.com) where it can be located by selecting Wind Engineering...Volume 1b...Data Item 01008...Abstract. The program can then be run as described in Section 3.1.

* On disk, Version 1.0 of the program is supplied in a zipped format as E0108V10.exe that will be automatically unzipped if installed using ESDUview or can be unzipped by running the file and copying to an appropriate location.

TABLE 3.1 Summary of Input Data for Worksheets "Reference site" and "Target site"

Reference site Worksheet Cell/Row No.	**Input entry**	**Target site Worksheet** Cell/Row No.	For further guidance see:
Cell F3	Enter location name or source reference.	Cell F3	
Row 5	Case number refers to a particular calculation case.	Row 8	
Row 6	Wind direction for Case (degrees from North). Direction from which the wind is blowing.	Row 9	
-	On Target site Worksheet, enter start Case number and end Case number for calculation run.	Cells D10, F10	
Row 8	Latitude of Reference site in degrees.	-	
Row 9	Reference wind speed from basic wind speed map or other source, or measured data (may include terrain changes and hill effects).	-	ESDU 82026[6]
Row 10	Gust averaging time, t. For fastest mile of wind, $t = 1609/ V_{ref}$ where V_{ref} is the fastest mile of wind in m/s.	Row 11	
Row 11	Height above ground (not zero plane).	Cell A11, A12, *etc*.	
Row 12	Height of zero plane above ground (accounts for upward displacement of wind profile due to ground obstructions). Typically, $d \approx 0.8 \times$ general level of obstructions for town centres and wooded terrain. See ESDU 82026 for more information.	Row 12	Sections 6.5
Row 13	If Reference site and/or Target site is on hilly terrain, check box (tick will appear) on relevant sheet.	Row 13	
Row 19	n_{ref} and n. Number of terrain roughness changes upwind of Reference site and Target site respectively.	Row 21	Section 4.3
Row 20	Terrain roughness (z_0 in metres) in 1st patch of terrain (x) between site and 1st roughness change upwind.	Row 22	Section 4.3
Row 21	Length of 1st patch (x) **in metres**.	Row 23	
Row 22	Terrain roughness (z_{01} in metres) in 2nd patch (x_1) between 1st and 2nd roughness changes upwind of site.	Row 24	
Row 23	Length of 2nd patch (x_1) **in metres**.	Row 25	
Row $(20{+}2n_{ref})$	Terrain roughness in final patch where equilibrium conditions assumed.	Row $(22{+}2n)$	Section 4.3
Row $(21{+}2n_{ref})$	Leave blank.	Row $(23{+}2n)$	
-	Calculation options are on Worksheet Target site . In column over Cells B1 to B7, choose one or more options by checking relevant boxes. To delete previous output, check last box; in this case, copy old results to separate Worksheet if so required.	Cells B1 to B7	
-	On completion of all input data, the Cases chosen are run by clicking the 'Run cases' button on Worksheet Target site .	Run button	

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TABLE 3.2 Summary of Topography Input Data

This Table relates to input data for the Worksheets ‘**Reference site topography**’ and ‘**Target site topography**’.

Cell /Row no.	Input entry	For further guidance see:
C4	Number of horizontal grid nodes; the default is 40.	Section 4.4.3
Row 22	Wind direction; degrees from North. Direction from which the wind is blowing.	
Row 23	Angle N0y; angle between North and the (minor) 0y hill axis.	Section 4.4.1(iii)
Row 24	Remaining input. If input data from Row 25 onwards is the same as another Case already input, that Case no. can be entered into Cell F24, J24, etc., as appropriate. This avoids re-entering the same input data (but see Section 4.4.1).	Section 4.4.1
Rows 25, 26	L_{01}, L_{02}, W_{01}, W_{02} . Enter half-height length scales in grey Cells C25 to D26 for Case 1, G25 to H26 for Case 2, *etc*. If these cells are left blank, the program will evaluate default values.	Section 4.4.1(iv) Section 4.4.2.1
Row 26	x_{peak} , y_{peak} . Enter coordinates of the local peak on which site is located into blue Cells E26, F26 for Case 1, Cells I26, J26 for Case 2, *etc*. The local peak is not necessarily the highest peak where terrain with several peaks is under consideration.	
Row 27	H_{peak} . Enter height of the local peak on which the site is located in Cell F27 for Case 1, J27 for Case2, *etc*.	
Row 27	x_{site} , y_{site} . Enter coordinates of the site in green Cells C27, D27 for Case 1, G27, H27 for Case 2, *etc*.	Sketch 4.4
Row 29 onwards	y_{AB} , z_{AB} ; x_{CD} , z_{CD} . Enter coordinates of the hill profile along sections AB and CD respectively where A, B, C, D are the start and end points where the section profile meets the surrounding plateau levels. Start and end plateau levels need not be the same.	Section 4.4.1(vi) and Worksheet
Row 74	Wind direction components and hill profile plots are provided automatically for verification purposes. If separated flow is predicted to occur, the modification to the hill profile for computation purposes is shown on the profile plots subsequent to running the Case(s).	Section 5
	All length measurements are in metres. All heights here are relative to a common level defined by the user.	

4. INPUT DATA

The input data required relate to the Reference Site and to the Target Site. The Reference Site represents the conditions of the site for which a known reference wind speed applies (see Section 4.1). This may include topographic effects and/or several changes in terrain roughness upwind of the site.

The Target Site represents the site for which wind speeds and/or turbulence data are required to be calculated. These are determined from the given wind speed at the Reference Site taking into account changes in terrain roughness, topography, gust averaging time, *etc.* (see Section 4.2).

4.1 Terrain Input Data for Reference Site

Select the Worksheet “Reference site”. The spreadsheet in mostly self explanatory through the sketches displayed and the Notes which appear when the cursor is placed on a cell containing a red marker in the top right-hand corner.

A range of **Cases** may be dealt with in any one run but note that the Reference Site data for Case 1 corresponds to that required for Case 1 at the Target Site, etc.

The value of ‘**Wind direction**’ entered in Row 6 is not used by the program, it is used here simply as a description of the ‘Case’. Wind direction becomes important when entering topographic data.

Details of the **Reference wind speed** are entered into rows 9 to 12. Further description of this data is given in Section 4.1.1.

If the Reference Site is situated in hilly terrain then the relevant box must be checked in row 13 by clicking into the relevant cell. Details of the topography must then be entered into the “Ref. site topography” Worksheet (see Section 4.4).

Details of the terrain at, and upwind of, the Reference Site are entered into rows 19 onwards for each Case. Firstly, the number of roughness changes must be entered into row 19, and this must be compatible with the following entries giving details of the terrain changes. If incompatibility is found by the program, an error message is displayed; this is done to avoid misinterpretation of the input data by the user.

Values of the terrain roughness parameter (z_0, z_{01}, *etc.*) and their respective terrain patch lengths (x, x_1, *etc.*) are required corresponding to the types of terrain upwind. Sudden (step) changes in terrain roughness are assumed to occur. Guidance in choosing values of z_0 for various terrains is given in the Worksheet “Terrain roughness”. Section 4.3 provides more detailed guidance, particularly for cases where there is a significant variation in terrain roughness across a patch normal to the wind direction.

If the Reference Site is on a hill or in a valley the consequent topographic effect (speed-up factor) is taken into account by the program to produce an equivalent reference wind speed for flat terrain. The relevant box must be checked in Row 13 by clicking onto the appropriate cell. Select the “Ref. site topography” Worksheet tab and input the relevant data for the reference site topography. Again, the sketches and Notes attached to various cells will assist in understanding the input data required. Further description of the topography input data parameters is given in Section 4.4.

4.1.1 Reference wind speed

The Reference wind speed can be either a basic design wind speed for standard conditions or, for example, a measured wind speed for specified (non-standard) conditions.

By definition, a basic design wind speed is the wind speed at z_{ref} over uniform terrain, $z_{0_{ref}}$, where there are no roughness changes upwind within at least 50 km. It is either an hourly-mean wind speed (for which t_{ref} = 3600 s), or a t-second gust. The reference wind speed is derived from a basic wind speed taken, for example, from a national map of basic design wind speeds for basic conditions (typically these are z_{ref} = 10 m and z_{0ref} = 0.03 m for open country terrain). To obtain the appropriate input value, V_{ref}, the basic wind speed should be multiplied by factors to account for departure from the basic conditions. The factors are as follows.

(i) A statistical factor to account for an annual risk of exceedance that is different from that applicable to the basic wind speed (see ESDU 82026[6]).

(ii) A directional factor, if available, to account for the variation of V_{ref} with wind direction (see ESDU 82026 for UK values).

(iii) A site altitude factor to account for the general level (above sea level) of the surrounding terrain at the site. Typically the factor is $(1 + 0.001\ h_{site})$ where h_{site} is the site altitude in metres. Note that when the site is located on a topographical feature, such as a hill, the site altitude factor is only greater than unity if the hill is superimposed on terrain where the general level for several kilometres around is above mean sea level. The topographical effect due to the hill site rising above the surrounding terrain is accounted for separately in the program.

However, in general, the Reference wind speed can either be an hourly-mean or gust speed and can apply to terrain with upwind terrain changes and with topographic effects due to hilly terrain. The program will correct the Reference wind speed to apply to flat terrain with no roughness changes and to a standard value of z_{0ref} = 0.03 m to obtain the required details at the Target site.

4.2 Terrain Input Data for Target Site

The input parameters on the "Target site" Worksheet are similar to those for the Reference site but, additionally there are menu options for the output parameters to be calculated and an input column for the heights above ground at which the calculations will be made. (Note that a zero height is not allowable; a minimum height of $2z_0$ is recommended.) Also, it is on this Worksheet, in cells D10 and F10, that the range of Cases to be calculated is entered (*e.g.* Cases 1 to 1 or 3 to 5, *etc.*).

The calculation options are chosen by checking the appropriate boxes so that a tick appears.

The terrain roughness details (z_0, z_{01}, z_{02}, *etc.*) and the corresponding terrain patch lengths (x, x_1, x_2, *etc.*) upwind of the Target site need to be entered for each Case (see Section 4.3)

If the Target site is hilly, then the corresponding boxes in row 13 need to be selected (ticked) and the topography data entered into Worksheet "Target site topography" (see Section 4.3).

Once all the required input has been entered, the computation of the range of chosen Cases is executed by clicking on the "Run cases" button.

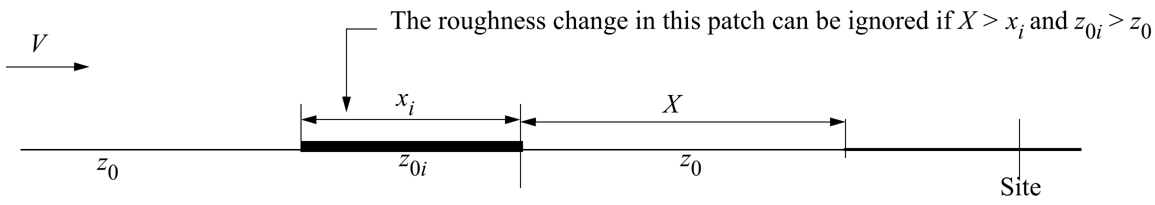
4.3 Terrain Roughness and Patch Length

Patch length (x, x_1, *etc.*) is defined as the length of a region of essentially constant terrain roughness upwind of the site. In assessing the values of z_0, z_{01}, *etc.* for a patch, it may also be necessary to take into account lateral variations in roughness normal to the wind direction; guidance on this is given in Section 4.3.1.

Typical values of the parameters z_0, z_{01}, *etc.* can be obtained from the Worksheet "Terrain roughness".

Beyond about 2 km upwind from the site it is usually only necessary to take into account major roughness changes such as at the coast or at the edge of built-up areas extending more than about 1 km in the wind direction.

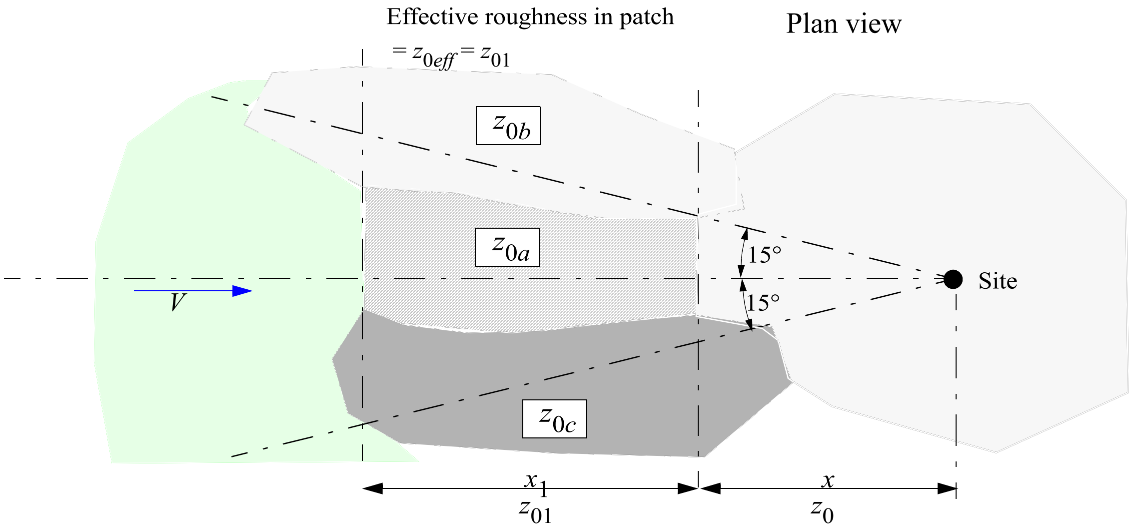
For the patch furthest upwind of the final roughness change (for 2 roughness changes this would be x_2) it is assumed that the patch length is sufficiently long for equilibrium conditions to have been established, and it is not necessary to enter a distance. In theory, this should be at least 30 km with no terrain changes occuring but this situation rarely occurs in practice. However, a simplification can be made, as illustrated in Sketch 4.1, that a roughness change due to a patch x_i of a roughness z_{0i}, embedded in an otherwise uniform terrain of smaller roughness (z_0), can be ignored if the distance (X) downwind of the patch is of length x_i or greater. This would apply, for example, to a small town in otherwise open country terrain.



Sketch 4.1 Simplification of terrain description

Because ‘sea’ terrain roughness is dependent on wave height which is strongly influenced by wind speed, sea surface z_0 varies from approximately 0.0001 m for typical strong winds to about 0.01 m for the highest design wind speeds. Since the local wind speed is not usually known initially, an iterative procedure is built into the program to estimate sea surface z_0 (see Section 6.1.1) and it is only necessary to type water or sea in the appropriate cell for z_0 for those patches involving a marine environment. The same procedure may also be used for stretches of inland water.

4.3.1 Lateral variation of terrain roughness in a patch



Sketch 4.2 Definition of terrain region in a patch affecting conditions at site

Depending on the lie of the terrain and wind direction, the terrain roughness in a patch may vary significantly in the direction normal to the mean wind direction giving regions of differing terrain roughness values.

Such an example is illustrated in Sketch 4.2 for the patch upwind of the first step change in z_0. Due to the lateral diffusion of shear stress and turbulence, conditions at the site are affected by terrain within the area bounded by the ±15° wedge shape. The patch x_1 contains terrain of roughnesses z_{0a}, z_{0b} and z_{0c}. An effective roughness (z_{0eff}) for this patch is estimated by averaging the individual shear stresses generated at ground level by each roughness category in the patch, and then evaluating the value of z_{0eff} that would generate the same average shear stress. This is derived in Section 6.1.2.

An Excel macro is provided in Worksheet "Terrain roughness" to calculate z_{0eff} for individual patches by inputting the values z_{0a}, z_{0b}, *etc.* and the respective fractions (A_a, A_b, *etc.*) of the total patch area covered by each roughness category. Note that $A_a + A_b + ... = 1$. Up to 4 different roughness categories can be entered.

The general procedure for determining the patches (x, x_1, *etc.*) is thus as follows.

(1) On a map mark the position of the ±15° lines of influence emanating from the site.

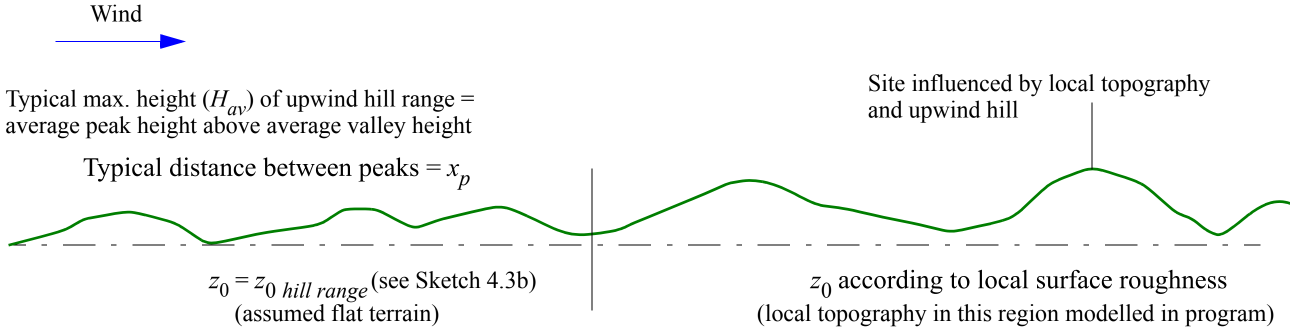
(2) Determine the patch lengths defined by step changes in roughness along the wind path using the roughness category covering the largest part of the area to define the roughness change.

(3) Within each patch, evaluate z_{0eff} (if necessary) using the Excel macro in Worksheet "Terrain roughness". To avoid an unnecessary complex assessment, only include terrain categories that exceed about 20% of the total patch area; if less than this, add the area to to the region with closest value of z_0 that is to be included.

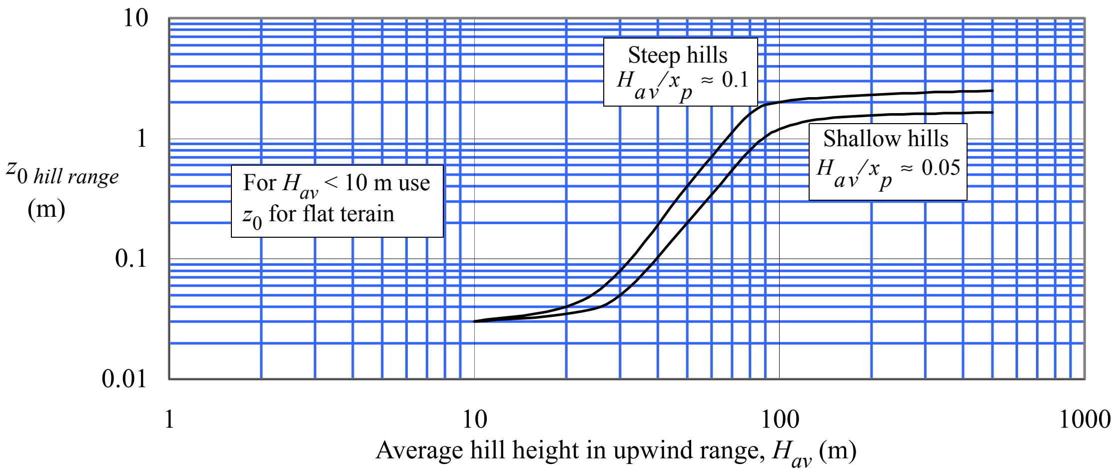
The example in Section 7 illustrates a case where an assessment of z_{0eff} is more important. However, in many cases this calculation is not necessary, particularly when the distance from the site is greater than about 5 km and an overall assessment can be made by inspection.

4.3.2 Inhomogeneous terrain

The effects of terrain roughness (z_0) for the case when the site is located on a hill or in a valley, are determined as if the site was on flat terrain. When there are ranges of hills upwind of the site, momentum is extracted from the wind and this effect can be represented by assigning this patch of terrain a roughness value ($z_{0hill\ range}$) dependent on the typical maximum height of hills in the patch along the wind direction, and their steepness. Approximate values of $z_{0hill\ range}$ are given in Sketch 4.3b based on a value used by the UK Met. Office for the Welsh hills (z_0 = 1.5 m) and data in Reference 15 for relatively steep terrain; these values are extrapolated to $H_{av} \rightarrow 0$ to ensure continuity. Close to the site, however, the local value of z_0 must be assigned a value appropriate to the local terrain, for example, z_0 = 0.01 m for typical grassland terrain on hills.



Sketch 4.3a



Sketch 4.3b Effective terrain roughness for complex terrain

4.4 Topography Input

The following notes refer to topographic input data for both the Reference Site and Target Site.

The first part of the program calculation involves the estimation of the topographic factors assuming two-dimensional flow along each of the principal orthogonal sections (*e.g.* AB and CD, see Sketch 4.4.) ‘Secondary three-dimensional’ corrections are then applied, dependent on the geometric parameters L_{01}, W_{01}, L_{02}, W_{02} (see (iv) in Section 4.4.1) and the site position relative to the summit. These secondary corrections are relatively small, particularly at locations well away from the summit, and so, even when the topography is irregular, it is not necessary to be very precise in determining these geometric parameters. For a specified intermediate wind direction, the wind speed perturbations and direction deviations for these two sections are superimposed vectorily to give speed-up factors for the inclined wind.

4.4.1 Isolated hills or valleys

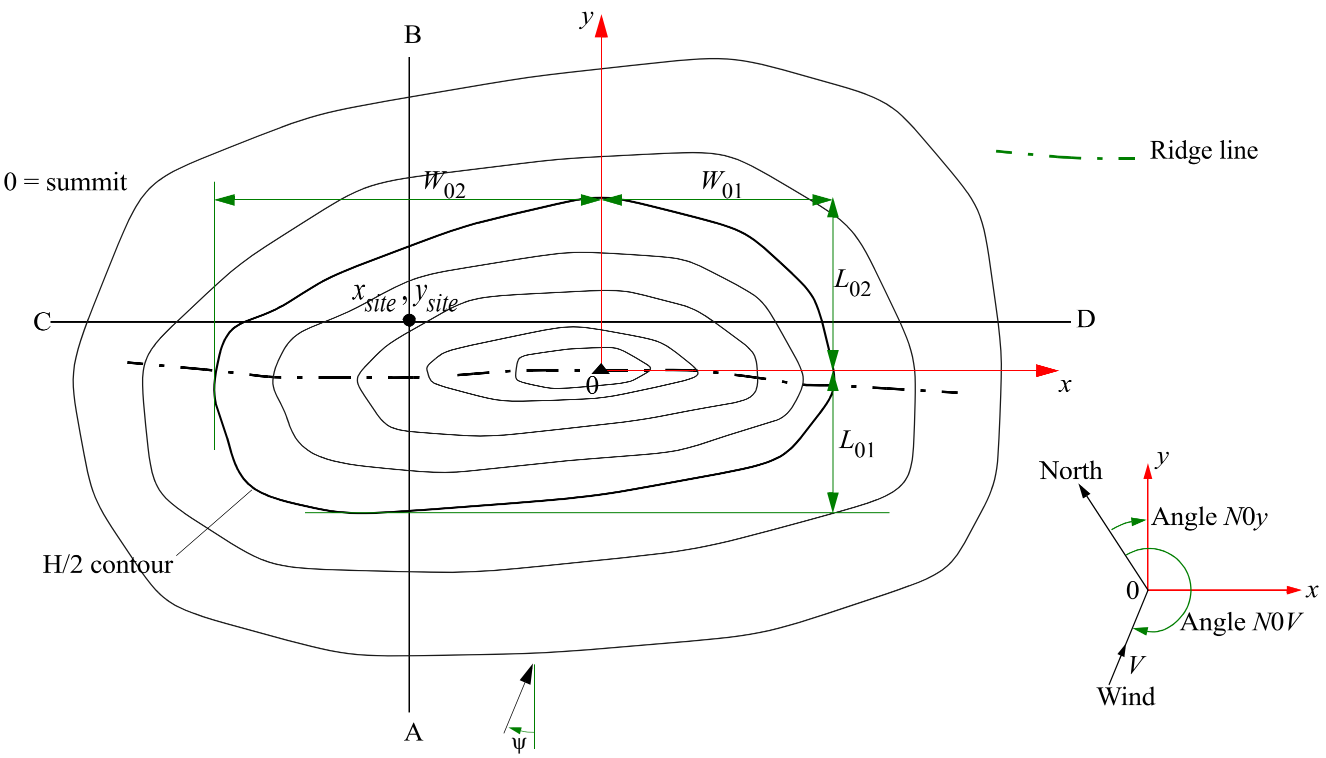
For a given site location it is necessary to plot out the hill (or valley) cross-sectional shapes along orthogonal axes AB and CD through the site (with AB normal to the local ridge line, see Sketch 4.4) and to determine hill planform parameters that characterise its overall shape.

The set of input data that follows applies for all wind directions; it only requires changing if an alternative site location is considered. The parameters involved are defined in Sketch 4.4 and are obtained as follows for an isolated hill (or valley); for more complex topography, see Section 4.4.2.

(i) Wind direction (degrees from North) is important in the case of topography.

(ii) Define the ridge line which, for the present purpose, is defined as the locus of those pairs of points furthest apart on each contour line (see Sketch 4.4). In some cases this is difficult to define (*e.g.*, when the length and width of a hill are nearly equal). In this case the ridge line is to be taken as the line joining the pair of points that are furthest apart on the half-height contour line.

(iii) The axes 0x and 0y and the angle N0y (see Sketch 4.4) are obtained as follows. Draw local orthogonal axes AB and CD passing through the site with AB crossing the major axis of the hill, normal to the local ridge line. The hill axes 0x, 0y are then drawn parallel to CD and AB passing through the summit, 0. The clockwise angle of the 0y axis from North is then given by the angle $N0y$.



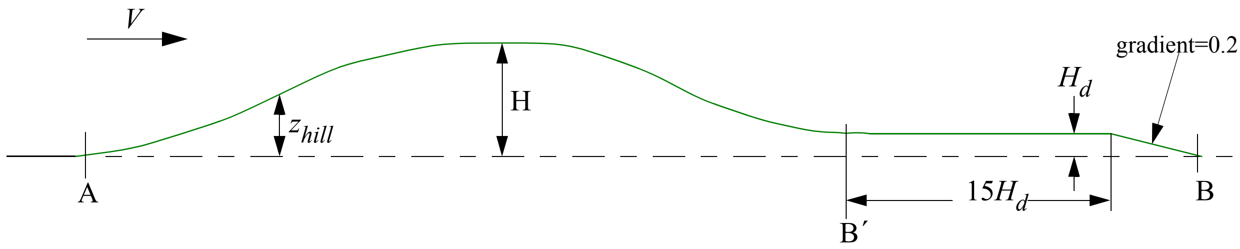
Sketch 4.4 Definition of topography axes, dimensions and angles

(iv) If the topography is not two-dimensional, the distances L_{01}, W_{01}, L_{02}, W_{02} from the summit to the half-height contour are required, as shown in Sketch 4.4. (Note that, for a given hill and given site location, the parameters L_{01} to W_{02} are only input for the case $\psi = 0$ as shown in Sketch 4.4; for other wind directions the program automatically chooses the appropriate values.)

Alternatively, the program will calculate default values of these parameters if one or more of the cells for these entries are left blank. When the site is close to the hill summit, the automatic evaluation of these parameters from the data inputs for sections AB and CD is a good approximation. If the site is located well away from the summit then errors in estimating these parameters are likely to occur if the topography planform is of an irregular shape. However, because the secondary three-dimensional effects are small, these possible errors in the geometric parameters will not have a significant effect on the calculation of either wind speed or its direction

(v) Determine the site coordinates, (x_{site}, y_{site}), along axes 0x and 0y.

(vi) Plot out the cross-sectional shapes along AB (and CD if the topography is not two dimensional) and from these plots define the position of the start and end points (A, B, C, D) of the topographic shape ($z_{hill} = 0$). Read off sufficient pairs of hill coordinates along AB and CD to define the respective section shapes and enter these under y_{AB}, z_{AB} and x_{CD}, z_{CD} as appropriate. The points do not have to be equally spaced and local hill heights are relative to a reference level, such as sea level or plateau level. When the outer plateau levels at each end of the hill are not equal, the program makes an adjustment, as described in the following note. The final coordinates to be input in this case are those for the point terminating the hill shape (point B′ in the example of Sketch 4.5).



Sketch 4.5 Computational model for case when upwind and downwind plateaux are of unequal height

For computational purposes, it is assumed that there is a level plateau upwind and downwind of the topographic shape and that these plateaux are at the same height. If this is not so then, for computational purposes, the program extends the downwind plateau from B′ (as illustrated in Sketch 4.5) and terminates it with a ramp down to (or up to) the upwind plateau level. This ensures that the added ramp, necessary to terminate the section shape (now AB), does not have a significant effect on the subsequent calculations at the site. No adjustment is required by the user.

If the column under z_{CD} is left blank (or the first cell under z_{CD} is blank) the program assumes that the topography is two dimensional.

Note that the program requires an odd number of pairs of points. The coordinates of points where z_{hill} is a maximum (or minimum if a valley) should be included. Points do not have to be entered in any particular order on the Worksheet; when the program is run these are automatically sorted into increasing values of x and y. However, for checking purposes, graph plots of the input section shapes are automatically produced (near row 80) as the data are entered and the section shapes will only be correctly reproduced (at data entry) when the points are in increasing order of x and y. The shapes are redrawn correctly after the program is run.

For cases where the wind direction is within ±15° of the axis AB (*i.e.*, nearly normal to the major axis of the hill) there is no need to enter hill section data for the orthogonal axis CD providing the half-height length scales (L_{01}, L_{02}, W_{01}, W_{02}) are input. In this case type 3D (or 3d) into the first cell under the column headed z_{CD} in Row 29. This ensures that the topography is not treated as two dimensional (as it would be if this cell is left blank) and three-dimensional corrections are applied as appropriate.

Where the topography data for a particular Case is the same as a Case already entered (wind direction changing only) there is no need to re-enter the topographic data. Furthermore, if such Cases are run simultaneously, the program avoids the time-consuming re-computation of hill speed-up factors for the same principal wind directions; the program applies a correction factor to a previously calculated run that accounts for any change in wind speed upwind of the hill. This correction factor accounts for any change to the blockage effect that the hill (not a valley) imposes on the overall upwind boundary layer (the height of which is dependent on the upwind wind speed). If such a Case is run independently, slightly different output values may result (typically up to about 2% in wind speed for a 60% change in reference wind speed)) because of the approximation inherent in the correction factor approach.

4.4.2 Complex terrain: terrain with several peaks

For the two-dimensional terrain calculation, the program automatically deals with topography having multiple peaks although, in modelling the topography in such cases, simplification can usually be made as indicated by Section 4.3.2. Appropriate evaluation of the three-dimensional parameters L_{01}, W_{01}, L_{02}, W_{02}, is not as obvious as in the case of an isolated hill (or valley) and Section 4.4.2.1 describes how this is covered.

When there are ranges of hills upwind of a site on a hill (Sketch 4.3a) it is usually only necessary to consider the hill just upwind (and downwind) of that on which the site is located. The effect of upwind ranges of hills is to extract momentum from the wind and this effect can be represented by assigning this patch of inhomogeneous terrain a high roughness value, for which guidance is given in Section 4.3.2. Close to the site, however, the local value of z_0 must be assigned a value appropriate to the local terrain, for example, $z_0 = 0.01$ m for typical grassland terrain on hills.

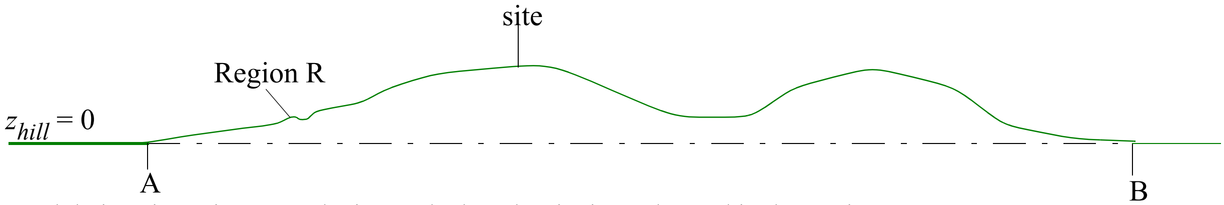
4.4.2.1 Three-dimensional parameters for complex terrain

In practice, the peak nearest to the site in question should be used as the reference point for determining the geometric parameters L_{01}, W_{01}, L_{02}, W_{02} as this, in general, will have the largest influence in determining the secondary three-dimensional effects. In many cases, the determination of these parameters will not be obvious and for this reason a set of rules has been built into the program so that these parameters can be evaluated automatically. This is not an exact process but, because the secondary three-dimensional effects are small, substantial discrepancies in these parameters will not lead to significant errors in the topographical speed-up factors. The coordinates of the peak (or valley base) of the local hill on which the site is located also need to be entered; these are relative to the $0x$ and $0y$ axes defined in Sketch 4.4.

The program will calculate appropriate values of L_{01}, W_{01}, L_{02} and W_{02} if the cells on the topography input sheets are left blank, and then write these values back to the corresponding blank cells. If values are input by the user, the program will use these values. In this way, it is possible to evaluate the effect on wind speed (and direction) of assuming other values of these input parameters, if so desired.

4.4.3 Grid size for computation

In order for the program to evaluate topographic effects, a calculation grid is superimposed on the terrain. The positioning of the grid and its overall size is determined by the program and local hill heights at these grid points are determined by interpolation of the input data, which are curve-fitted by the program. The default value for the horizontal grid is 40 steps but this can be changed by the user by entering a value in Cell C4 on the topography input worksheets. The grid spacing, which is uniform, may need to be changed by the user in order to ensure that particular features of the topography are included in the computation. The horizontal spacing is given by the horizontal length of the section shape (sections AB, CD, see Sketch 4.6) not including the plateau lengths, divided by the number of horizontal grid nodes.



Undulations in region R can be ignored when the site is not located in that region.

Sketch 4.6

Note that for regions of the topography removed from the site under consideration, such as region R in Sketch 4.6, it is not necessary to model small variations in the topography section shape; they will have an insignificant effect on conditions at the site illustrated. As a guide, if the site is not located on a small bump or dip superimposed on the general hill shape, it is not necessary to increase the number of horizontal grid points to include these undulations in the computation.

The vertical grid spacing is dertermined entirely by the program and is logarithmic in form, giving smaller spacings near ground level where more rapid changes in the speed-up factor occur.

5. OUTPUT DATA

Wind speed (hourly-mean and *t*-second gusts if requested) are output to Worksheet “Wind speeds”. Where data cannot be calculated (for example, inside a region of separated flow near the ground over a steep hill), an asterisk (*) is printed.

If steep terrain is involved and flow separation is predicted to occur somewhere over the terrain in question, an indication of this is given on the Worksheet “Wind speeds”. The user is then recommended to return to the input Worksheet “Target site topography” where for the Case, or Cases, calculated the assumed separated flow regions are superimposed on the graphs showing the hill section shapes. If a separated flow region is comparatively large and includes the site location then greater uncertainty in the results must be expected. The uncertainty will be correspondingly smaller when the separated flow region is further from the site.

Where topographic effects occur at the site in question, mean flow deviation angles from the oncoming wind direction are output onto Worksheet “Flow deviations”. If positive, the deviation is clockwise from the oncoming wind direction.

Corresponding output data for turbulence properties are given in separate Worksheets “*u*-component turbulence”, “*v*-component turbulence” and “*w*-component turbulence”.

Spectral density data for the *u*-, *v*-, and *w*-components of fluctuating wind speed are given in Worksheet “Spectral densities”.

6. BASIS OF THE METHODS

Wind and turbulence properties are influenced by the following parameters:

(i) height above the ground,

(ii) ground roughness at the site,

(iii) changes in ground roughness upwind of the site,

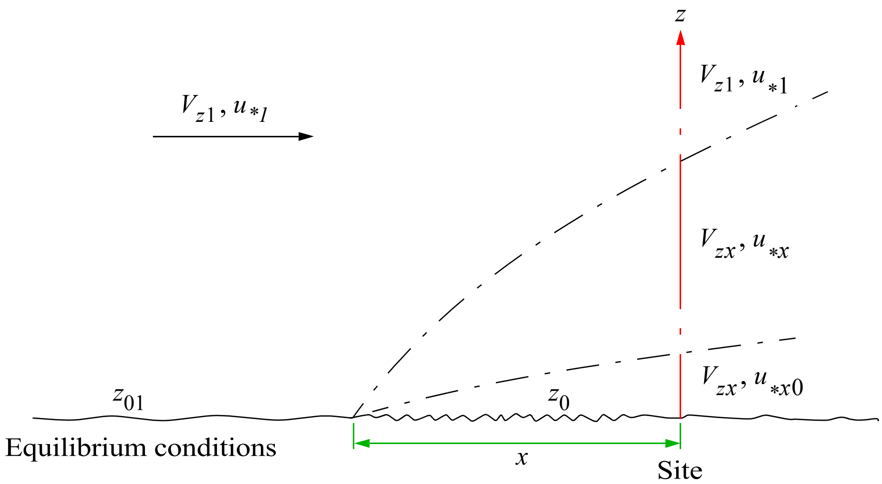
(iv) topographic effects such as caused by hills,

(v) for gusts, averaging time.

These effects are quantified in ESDU 82026[6] (hourly-mean wind speed), 83045[7] (gusts) and ESDU 85020[12] and 86010[13] (turbulence intensity, integral length scales and spectral density). The methods given in those Items are based on the Deaves/Harris models[1, 3, 4] for mean wind speed and turbulence properties. In some instances the methods have been modified to take into account more recent developments and, in the case of integral length scales of turbulence, extended to account for the important effect of ground roughness changes upwind of the site.

The Excel program is based on the full Deaves/Harris model rather than the simplified methods but the improvements and extensions to the model mentioned above have been retained. The user is referred to the original Data Item sources for the details of the models but Sections 6.1 to 6.7.2 summarise the principal derivations. Section 6.6 briefly describes how the basic methods, which are strictly applicable only to a single roughness change, have been extended to apply for cases involving multiple roughness changes.

6.1 Hourly-mean Wind Speed, V_{zx}



Sketch 6.1 Site with single roughness change upwind

The equations giving the variation of hourly-mean wind speed with height over uniform terrain with no roughness changes within about 50 km of the site (equilibrium conditions) are summarised in Appendix A of Item 82026.

The effect of a single roughness change on V_{zx} is given by the method of Deaves and Harris[1, 3] modified to take into account the fact that it gives an increasing (but relatively small) error as the patch x increases beyond about 3000 m when a matching length parameter, l_0, is greater than about 0.1 h. Because other relationships given by Deaves and Harris provide the 'correct' asymptotic solution for $x = F$ (the equilibrium fetch) a correction factor (K_u) operating on $u_{*xo}/u_{*1} - 1$ can be derived for $x = F$. A variation of K_u is then defined so that $K_u \to 1.0$ for values of l_0/h less than about 0.1 and $u_{*xo} \to u_{*1}$ as $x \to F$. The original equations giving u_{*xo} are:

$$\frac{u_{*xo}}{u_{*1}} = 1 - \frac{\ln(z_{01}/z_0)}{\ln(1 + l_0/z_0) + 0.42} \tag{6.1}$$

with $$(1 + l_0/z_0)[\ln(1 + l_0/z_0) - 1] = 0.32\, x/z_0 \,. \tag{6.2}$$

Equations (6.1) and (6.2) can be closely approximated by Equation (6.3) with $K_u = 1$. Introducing K_u provides the correction described above so that

$$\frac{u_{*xo}}{u_{*1}} = 1 - \frac{K_u \ln(z_{01}/z_0)}{0.0106[\ln(x/z_0)]^2 + 0.610\ln(x/z_0) + 0.316} \tag{6.3}$$

with $$K_u = \exp[-0.0008\{7 + \ln(x/F)\}^{4.5}] \tag{6.4}$$

and $$F = 0.358(u_*/f)^{4/3} z_0^{-1/3} \quad \text{for } z_0 \geq z_{01} \tag{6.5}$$

or $$F = 2.33(u_*/f)(z_{01}/z_0)^{1/2} \quad \text{for } z_0 \leq z_{01} \,. \tag{6.6}$$

6.1.1 Water surface z_0

The terrain roughness parameter for a sea (or water) surface varies with wind speed and cannot therefore be determined directly unless the local wind speed is known initially. In ESDU 82026 an equation is given relating z_0 to u_{*r} for a reference terrain of $z_{0r} = 0.01$ m. For convenience of use, this equation was fitted to a more fundamental relation,

$$z_{0sea} = u_*^2/600 \text{, or } 5 \times 10^{-5} \text{ m} \quad \text{whichever is the larger,} \tag{6.7}$$

where u_* is the local friction velocity at the surface. This equation is used in the iterative procedure built into the program to evaluate sea surface z_0 for the calculated local friction velocity. It can also be used as a reasonable approximation for stretches of inland water.

6.1.2 Effective roughness of terrain patch

The effective average roughness of a patch of terrain in which there is a significant variation in z_0 in the across-wind direction, as described in Section 4.3.1, can be derived as follows. As illustrated in Sketch 4.2, each area of terrain of roughness z_{0a}, z_{0b}, *etc.* within a patch generates shear stresses (τ_a, τ_b, *etc.*) at the site. The average shear stress is given by

$$\tau_{avg} = A_a\tau_a + A_b\tau_b + A_c\tau_c + \ldots = \rho u_{*\,eff}^2 \tag{6.8}$$

where A_a, A_b, *etc.* are fractions of the total patch area, ρ is air density and $u_{*\,eff}$ is the effective value of friction velocity. Assuming local equilibrium conditions, the ratios

$$\frac{u_{*a}}{u_{*b}} = \frac{\ln(10^5/z_{0b})}{\ln(10^5/z_{0a})} = K_{ab}\ ,\quad \frac{u_{*a}}{u_{*c}} = \frac{\ln(10^5/z_{0c})}{\ln(10^5/z_{0a})} = K_{ac},\ etc. \tag{6.9}$$

(given as approximations in ESDU 82026) can be substituted into Equation (6.8) to give

$$\frac{u_{*eff}}{u_{*a}} = \left[A_a + \frac{A_b}{K_{ab}^2} + \frac{A_c}{K_{ac}^2} + \ldots\right]^{1/2} = \frac{\ln(10^5/z_{0a})}{\ln(10^5/z_{0eff})} \tag{6.10}$$

so that

$$\ln z_{0eff} = \ln 10^5 - \frac{\ln(10^5/z_{0a})}{\left(A_a + \dfrac{A_b}{K_{ab}^2} + \dfrac{A_c}{K_{ac}^2} + \ldots\right)^{1/2}}. \tag{6.11}$$

6.2 Gust Speed

The relationship between gust speed, V_{gx}, and mean wind speed, V_{zx}, for varying gust averaging time, t, is derived in ESDU 83045[7]. The equation used in the program for the peak factor g (which is an adequate fit to Figure 2 of ESDU 83045) is

$$g = 4.2\exp\left[-(0.08t_1^3 - 0.17t_1^2 + 0.3t_1)\right], \tag{6.12}$$

where $t_1 = 1 + \log_{10} t$.

Then $V_{gx}/V_{zx} = 1 + gI_{ux}$

6.3 Turbulence Intensities for Flat Terrain

The equations used to calculate I_u, I_v and I_w for equilibrium conditions are summarised in ESDU 85020[12].

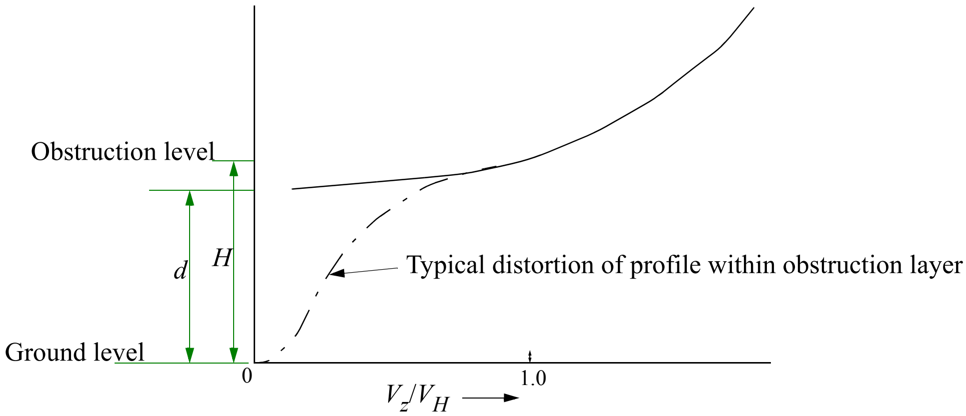
The effect of a single roughness change on σ_u to give σ_{ux} is provided by Deaves[4] and this method is incorporated directly into the program. The intensities of turbulence are evaluated directly as $I_{ux} = \sigma_{ux}/V_{zx}$, $I_{vx} = \sigma_{vx}/V_{zx}$ and $I_{wx} = \sigma_{wx}/V_{zx}$.

6.4 Integral Length Scales

The model giving ${}^xL_u$ for equilibrium conditions at a site is described in ESDU 85020[12]. The scheme for estimating the effect of upwind roughness changes on ${}^xL_u$ is summarised in Appendix A of ESDU 85020 (Amendment C). This involves using local values of V_{zx} (and $\mathrm{d}V_{zx}/\mathrm{d}z$), u_{*x} and σ_{ux}. Equations relating all other length scales to ${}^xL_u$ are summarised in ESDU 86010[13].

6.5 Values at Heights Below the Zero-plane Displacement

For built-up sites, or sites with a large number of trees, there is an upward displacement of the effective ground level where mean wind speed tends to zero. The mathematical models used in the program apply providing $z_g > d$ (the zero-plane height above ground level). Sometimes it may be necessary to make an estimate of wind speed or turbulence properties below the zero-plane level. To facilitate this, the program incorporates some simple extrapolation rules for heights less than $1.2d$ but these data should be used with extreme caution because of large variations caused by surface obstructions at heights close to the ground. The output tables from the program have a warning to this effect.



Sketch 6.2 Distortion of mean wind speed profile within a uniformly-distributed surface roughness

The extrapolations used for heights less than 1.2d are as follows.

(1) For mean wind speed the variation with height below z_g = 1.2d is distorted to follow the typical variation shown in ESDU 82026 (see Sketch 6.2). The distorted profile is such that, at z_g = 1.2d, the values of V_z and dV_z/dz are the same as for the undistorted profile.

(2) For intensity of turbulence (σ_i/V_z), values of σ_u, σ_v and σ_w are assumed constant for $z_g < 1.2d$.

(3) Integral length scales of turbulence are distorted below z_g = 1.2d so that they tend to zero as $z_g \rightarrow 0$.

6.6 More Than One Roughness Change

The Deaves/Harris models provide relationships for estimating local wind speed and turbulence properties when there is a single roughness change upwind of the site. These relationships can be used to generate data for cases involving more than one roughness change by using the following procedure which approximates non-uniform terrain to a series of single roughness changes.

Starting with the roughness change furthest upwind from the site, values of the local parameters (u_{*x}, V_{zx}, σ_{ux} etc.) are calculated at the start of the next roughness change using the method for a single roughness change. These values are then used as the input parameters for the next change and the process repeated until all roughness change effects have been accounted for.

It is also assumed that the perturbation effects due to roughness changes and the perturbation effects due to topography are additive.

6.7 Topographic Effects

To a first approximation it has often been assumed that topographic effects only influence the mean wind speed and do not have an immediate effect on the rms fluctuating velocities $(\sigma_u, \sigma_v, \sigma_w)$ or on integral length scales. This is a reasonable assumption for topography with an upwind slope less than about 0.2 but is increasingly less valid for larger slopes and for heights close to the ground (less than about 10 m) where, in particular, σ_u is significantly magnified. Section 6.7.1 summarises the basis of the methods to account for the effect of topography on mean wind speed. Section 6.7.2 summarises the effect of topography on spectra and variances.

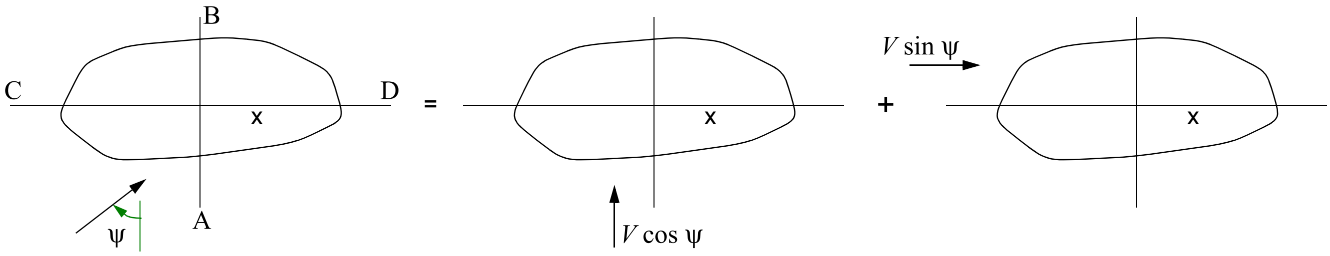
6.7.1 Topographic effects on mean wind speed

The effect of topography (hills and valleys) is taken into account by the computational method of Deaves[2] involving the solution of the two-dimensional Navier-Stokes equations governing flow in the atmospheric boundary layer. The method of Deaves has been used because it is compatible with Harris-Deaves mean wind speed model and gives results which compare favourably with measurements. The Deaves method only applies to two-dimensional flow but three-dimensional effects are usually small although not necessarily negligible. A simplified method for estimating the three-dimensional effects is described in Appendix A of ESDU 91043[17]. Essentially (for wind direction normal to a principal axis of a topographic feature), it takes the form

$$K_{L3d} = 1 + f_{ar} (K_{L2d} - 1) + \Delta K_{L3d} \tag{6.13}$$

where K_{L3d} is the speed-up factor at the point in question, K_{L2d} is the equivalent value calculated assuming two-dimensional flow, f_{ar} is a factor dependent on the hill effective aspect ratio (typical length/width) and ΔK_{L3d} represents the 'secondary three-dimensional corrections' (which are relatively small).

ESDU 91043 explains how simplified relationships for these factors have been derived using data generated from a more complex three-dimensional hill program. The calculation for an inclined wind (V) is based on the method of superposition in which the flow field vectors, generated by an incident wind $V\cos\psi$ along section AB (see Sketch 6.3) and $V\sin\psi$ along section CD are combined, taking into account flow deviations in each flow field.



Sketch 6.3 Superposition of flow fields for inclined wind

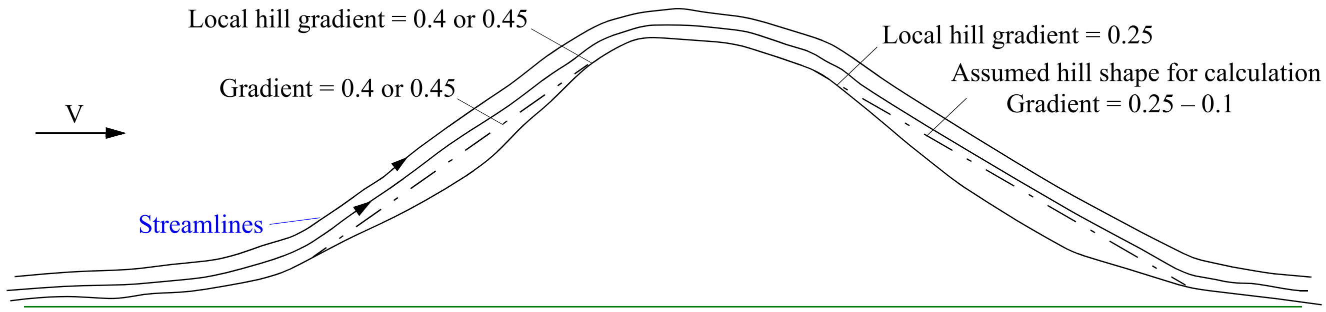
Other three-dimensional component corrections, such as those involving the position of the site relative to the summit of the hill, are built into the basic calculation for flow along the principal axes (AB, CD).

6.7.1.1 Steep topography, flow separation

From full-scale and wind-tunnel measurements, simplified criteria can be established for estimating when the flow around a hill will separate from the surface. Theoretically, it is the local adverse pressure gradient at the surface which principally determines the onset of separation but, in practice, the maximum surface slope of the hill can be used as a simpler, more easily evaluated, criterion. The following criteria are used in the program to establish the onset of flow separation.

Two-dimensional hill, upslope: maximum gradient = 0.4 (21.8°)
Two-dimensional hill, downslope: maximum gradient = 0.25 (14.0°)
Three-dimensional hill, upslope: maximum gradient = 0.45 (24.2)
Three-dimensional hill, downslope: maximum gradient = 0.25 (14.0°)

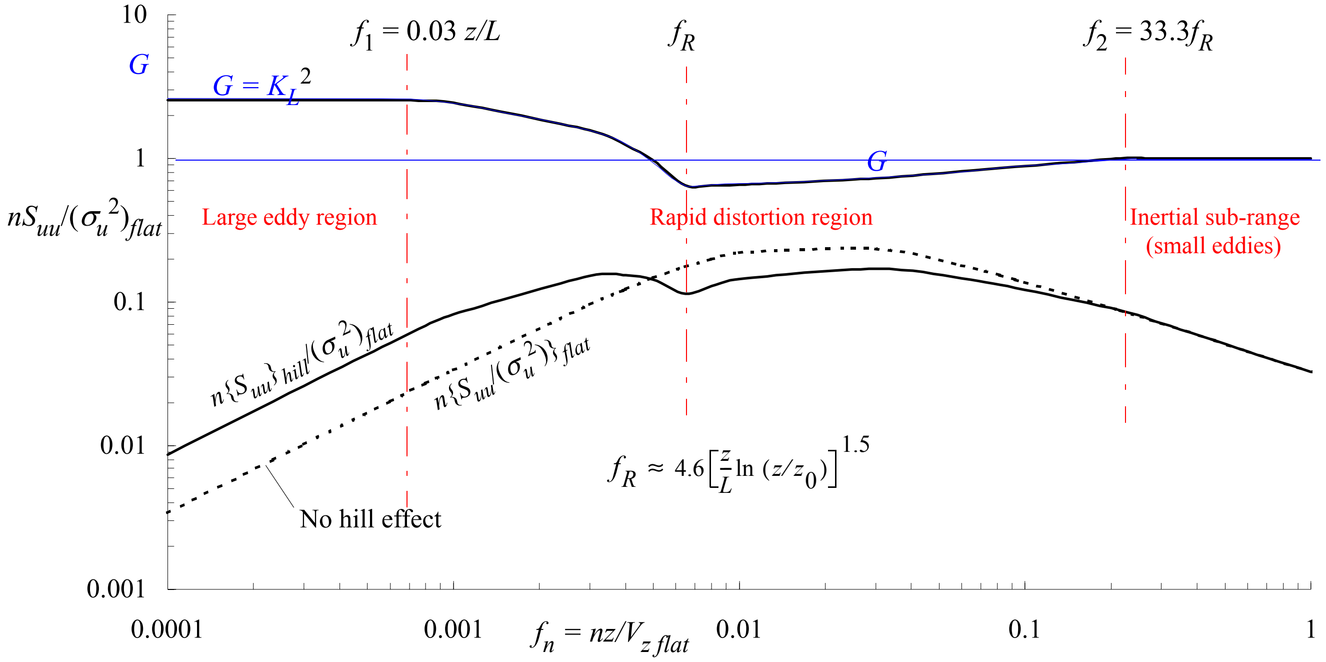
The program evaluates local surface gradients for the complete range of topography. Where the above criteria are exceeded the local surface is modified so that the local gradient does not exceed the following criterion. The modified surface is extended at the gradients noted above (but decreased on the downwind slope by approximately 6 degrees) until it meets the original hill surface on either the upwind slope or downwind slope as appropriate. The 6 degrees decrease is to aproximate the growth of the separation region from a surface of gradient 0.25 and this has the effect of increasing the separation region to an extent indicated by comparison with full-scale measured data (see Section 9). Above the separated flow layer, the local streamlines follow the modified hill contour as illustrated in Sketch 6.4 and this modified gradient is used to calculate the local speed-up factors. Within the separated flow region, an approximate estimation of mean wind speed is made based on typical empirical variations in this region but turbulence properties cannot be calculated. Note that, within a two-dimensional flow separation region, reverse flow occurs near the surface but in a three-dimensional flow this does not usually happen because of spanwise flow components; for the purpose of the present program, it is assumed that reverse flow does not occur.



Sketch 6.4 Hill with separated flow

6.7.2 Turbulence properties over hilly terrain

The modifications to turbulence properties (intensities and spectra) of the fluctuating components (u, v, w) of wind speed in the flow over a hill (with no extensive flow separations) are included in the Excel module. They are based on the guidlines provided by Frank[18] who provides a summary of various authors' research. The methods are approximate but provide corrections to spectra and variances which follow the trends exhibited by measured data.



Sketch 6.5 Illustration of distortion to S_{uu} in outer region ($z > h_i$) over a hill

The flow over a hill can be divided into inner and outer regions. The inner region is generally only a few metres thick and it is the outer region which is usually of more practical interest. The height (h_i) of the inner region can be approximated by

$$\frac{h_i}{L} \times [\ln(h_i/z_0)]^{1.5} \approx 0.32 \qquad (6.14)$$

where $2L$ is the width of the hill at half height in the wind direction. In Equation (6.14), the ln( ) term is raised to the power of 1.5, rather than 2, as suggested by Frank in his conclusions.

In the outer region (see Sketch 6.5) at low frequencies, the large eddies change in proportion to V_{hill}/V_{flat}. Therefore, for a given value of $(nz/V_{z\,flat})$ there is an increase in the spectral densities, S_{uu} and S_{vv}, typically by the factor $G = (V_{z\,hill}/V_{z\,flat})^2$ where $V_{z\,hill}$ and $V_{z\,flat}$ are the mean wind speeds locally on the hill and upwind of the hill respectively, at the same height above ground level. It is assumed that the only change to S_{ww} is that due to curvature and tilting of the streamlines[18]. At high frequencies, it is assumed that the spectra are in equilibrium with the upwind conditions and that there is no distortion so that $[S_{ii}]_{hill} = [S_{ii}]_{flat}$ and $G = 1$. At intermediate frequencies, rapid distortion theory shows that there is a general reduction in spectral density ($G < 1$) as eddies are stretched horizontally. This effect is quantified by Frank[18] at $f_n = f_R$ (see Sketch 6.5); values of G at other frequencies are interpolated by a cosine function of $\log f_n$ between f_1 and f_R and f_R and f_2 so that a smooth variation of S_{ii} with frequency is obtained.

In the inner region ($z < h_i/2$), an approximate assumption can be made that the $i = u$, v and w spectra exhibit local equilibrium conditions and that $G = (V_{z\,hill}/V_{z\,flat})^2$, giving $(\sigma_i^2)_{hill} = G.\,(\sigma_i^2)_{flat}$. For $h_i/2 < z < h_i$, a transition to outer layer conditions is interpolated on the basis of a cosine function of $\log z$.

The change to the respective variances, σ_{ii}^2 is given by

$$\frac{(\sigma_{ii}^2)_{hill}}{(\sigma_{ii}^2)_{flat}} = \frac{\int_0^\infty (G-1)(S_{ii})_{flat}\,\mathrm{d}f_n}{(\sigma_{ii}^2)_{flat}} + 1\,. \qquad (6.15)$$

The effects of streamline curvature and tilt are also considered by Frank; they are usually negligible for the u- and v-components but can be significant for the w-component. Convex curvature has a stabilizing effect on turbulence and *vice versa* for concave curvature; these effects are included in the Excel module. Eddy tilt effects are not included (for which, see Reference 18) but these are generally only important for the w component.

Calculations by Frank[18] compare reasonably well with full-scale measurements on a number of different hills. The calculations show a considerable increase in the variances in the lower half of the inner layer over the hill but, at greater heights, the ratio given by Equation (6.15) tends to unity comparatively rapidly, although intermediate values for the w-component may be slightly less than unity.

7. EXAMPLE

The following example illustrates many facets of the program, particularly those associated with topographic effects. The elements of the example are illustrated in Sketch 7.1.

A 65 metre high TV mast is to be erected on a hill site overlooking a small coastal town (latitude 50 degrees). Hourly-mean wind speeds and 3-second gusts at heights up to 65 m are required. The critical wind direction for wind loading is assessed to be in the southwest to west quadrant. The basic design wind speeds (z_{0r} = 0.03 m) at a height of 10 m, for the southwest and west directions, are evaluated to be 25 m/s and 23 m/s respectively. The general terrain is illustrated in Sketch 7.1. Details of the input data (both terrain and topography) are given in Figures 7.1 to 7.2. For the purposes of the example, wind directions only from the southwest and west will be considered; in practice, other directions should also be evaluated.

For the wind direction from the southwest, a case is run ignoring the lateral variations in terrain roughness. To illustrate the importance of "averaging" the upwind terrain for this site, the calculation is repeated (case 2) using values of effective roughness for each patch (assessed as described in Section 4.3.1) to allow for the influence of all terrain (within the ±15° boundaries) on conditions at the site .

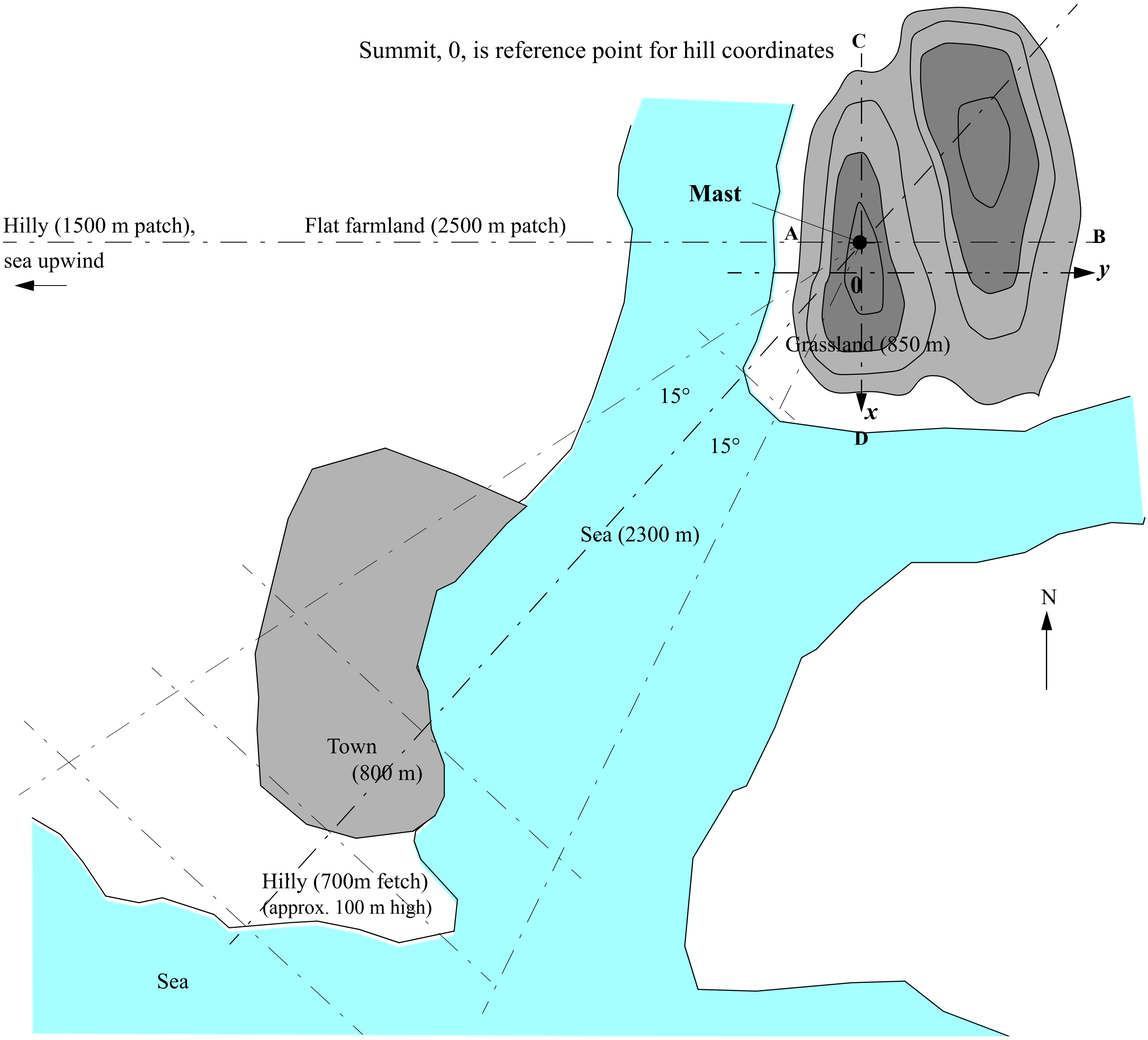
Wind from the southwest

In Figure 7.1, Case 1 is run for values of z_0 along the wind direction, not taking into account any lateral variation of terrain roughness. In Case 2, effective values of z_0 for each patch length are evaluated using the Excel macro on Worksheet "Terrain roughness" for the mix of terrain roughnesses given in Table 7.1.

TABLE 7.1

Patch length	z_{0a} (m)	z_{0b} (m)	z_{0c} (m)	A_a	A_b	A_c	z_{0eff} (m)
x	Grassland 0.01	Sea 0.0026		0.17	0.83		0.0034
x_1	Sea 0.0026	Town 0.3		0.85	0.15		0.0075
x_2	Town 0.3	Sea 0.0026	Hills (ht:100m) (Sketch 4.2) 1.0	0.62	0.25	0.13	0.16
x_3	Hills 1.0	Sea 0.0038		0.65	0.35		0.28

For the sea patches, the value of z_0 is taken from the initial run (Case1).

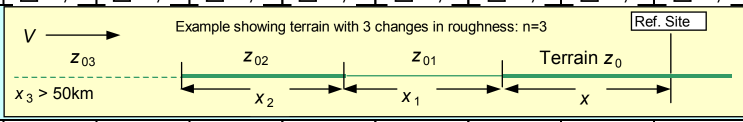


Sketch 7.1 Details of the terrain surrounding the site

The typical height of the hilly terrain (away from site area) is about 100 m with peaks about 2 km apart.

The value of z_0 for the sea areas is determined by the program in the runs for Cases 1 and 3; these values are output on Worksheet "Wind speeds" (Figure 7.3).

Calculated wind speed results are given in Figure 7.3.

	A	B	C	D	E	F	G	H	I	J	K
1	30/4/05 18:59										
2				REFERENCE WIND SPEED AND CORRESPONDING TERRAIN							
3				LOCATION/NAME: EXAMPLE CALCULATION							
4											
5		Case	1	2	3	4	5	6	7	8	9
6		Wind direction (degree from N):	225	225	270						
7		Range of Cases to be calculated:	As in Sheet "Target Site"								
8		Latitude (degree)	50	50	50						
9		Reference wind speed (m/s)	25	25	23						
10		If gust, averaging time (s)									
11		Ht above ground (m)	10	10	10						
12		Zero plane ht d (m)	0	0	0						
13		If hilly terrain at ref site, check box	☐ Hilly	☐ Hilly	☐ Hilly	☐ Hilly	☐ Hilly	☐ Hilly	☐ Hilly	☐ Hilly	☐ Hilly
14–18											
19		No. of terrain changes: n_{ref}	0	0	0						
20		Terrain roughness, z_0 (m)	0.03	0.03	0.03						
21		Patch length, x (m)									
22		z_{01} (m)									
23		x_1 (m)									

There are four roughness changes for each direction and "water" is input for each patch of sea.

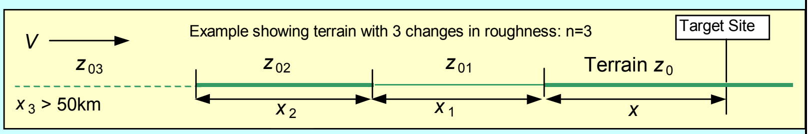
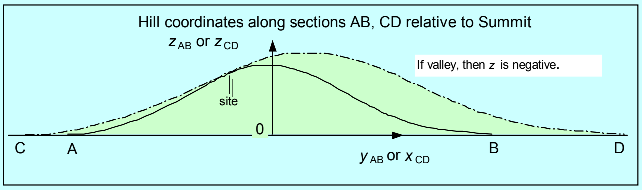
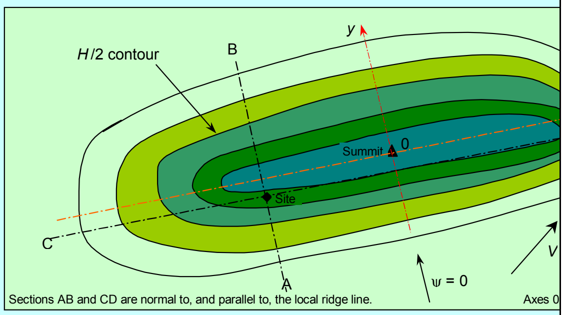
	A	B	C	D	E	F	G	H	I	J
1	30/4/05 18:59	Wind speeds are always calculated. Other calculation options:								
2	To calculate spectral densities (S_{uu} etc), enter frequencies on Worksheet 'Spectral densities'.				TARGET SITE DETAILS					
3		☑ I_u, ^xL_u, ^yL_u, ^zL_u, S_{uu}			LOCATION/NAME: EXAMPLE CALCULATION					
4		☐ I_v, ^xL_v, ^yL_v, ^zL_v, S_{vv}								
5		☐ I_w, ^xL_w, ^yL_w, ^zL_w, S_{ww}								
6		☐ On re-run, delete all old results								
7										
8	Heights above ground for calculations (m)	Case	1	2	3	4	5	6	7	8
9		Wind direction (degree from N):	225	225	270					
10		Range of Cases to be calculated:	Case No.	1	to	3				
11	3	If gust, averaging time, t (s)	3	3	3					
12	5	Zero plane ht, d (m)								
13	10	If hilly terrain at site, check box	☑ Hilly	☑ Hilly	☑ Hilly	☐ Hilly	☐ Hilly	☐ Hilly	☐ Hilly	☐ Hilly
14	20	If heights are changed in any way, check box (near cell B7) to delete old results on re-run. If so required, copy old results to a separate Worksheet or print them out.								
15	30									
16	40									
17	50									
18	65									
19										
20										
21		No. of terrain changes: n	4	4	4					
22		Terrain roughness, z_0 (m)	0.01	0.0034	0.01					
23		Patch length, x (m)	850	850	400					
24		z_{01} (m)	water	0.0075	water					
25		x_1 (m)	2300	2300	700					
26		z_{02} (m)	0.3	0.16	0.03					
27		x_2 (m)	800	800	2500					
28		z_{03} (m)	1	0.28	3					
29		x_3 (m)	700	700	1500					
30		z_{04} (m)	water	water	water					
31		x_4 (m)								

FIGURE 7.1 Input data: extracts from Worksheets "Reference site" and "Target site"

Values of the half-height parameters (L_{01}, L_{02}, W_{01}, W_{02}) are not input for this example; the program calculates default values.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1	30/4/05 18:59		**TARGET SITE: EXAMPLE CALCULATION**											
2			**TOPOGRAPHY INPUT DATA**											
3														
4		No. of horiz grid nodes for computing:	40											





	B	C	D	E	F	G	H	I	J	K	L	M	N
21	Case	1				2				3			
22	Wind direction (angle N0V deg from N)	225				225				270			
23	Angle N0y (degree)	90				90				90			
24	Remaining input	Remaining	input same	as Case:		Remaining	input same	as Case:	1	Remaining	input same	as Case:	1
25	L_{01} (m) L_{02} (m)	235.7	481.8	x_{peak} (m)	y_{peak} (m)			x_{peak} (m)	y_{peak} (m)			x_{peak} (m)	y_{peak} (m)
26	W_{01} (m) W_{02} (m)	302.4	644.8	0	0								
27	x_{site} (m) y_{site} (m)	-120	0	H_{peak} (m)=	88			H_{peak} (m)=				H_{peak} (m)=	
28	Section coordinates (m)	y_{AB}	z_{AB}	x_{CD}	z_{CD}	y_{AB}	z_{AB}	x_{CD}	z_{CD}	y_{AB}	z_{AB}	x_{CD}	z_{CD}
29	There must be an odd number	-500	0	-1200	0	-500	0	-1200	0	-500	0		
30	of points for each section.	-450	1.5	-1100	3.8	-450	1.5	-1100	3.8	-450	1.5		
31	Coordinates can be entered in any	-400	4.8	-1000	9.3	-400	4.8	-1000	9.3	-400	4.8		
32	order. The program sorts data into	-350	13	-900	19.8	-350	13	-900	19.8	-350	13		
33	increasing values of y or x.	-300	22.8	-800	30.2	-300	22.8	-800	30.2	-300	22.8		
34	All heights are referred to a common	-250	37.2	-700	38.2	-250	37.2	-700	38.2	-250	37.2		
35	user-defined level.	-200	49.3	-600	48.7	-200	49.3	-600	48.7	-200	49.3		
36		-150	60.6	-500	56	-150	60.6	-500	56	-150	60.6		
37		-100	70	-300	72	-100	70	-300	72	-100	70		
38		-50	78.6	-200	76	-50	78.6	-200	76	-50	78.6		
39		-20	80.8	-120	81.3	-20	80.8	-120	81.3	-20	80.8		
40		0	81.3	-40	87.2	0	81.3	-40	87.2	0	81.3		
41		50	80	0	88	50	80	0	88	50	80		
42		100	77	100	82.2	100	77	100	82.2	100	77		
43		150	72.1	200	68.2	150	72.1	200	68.2	150	72.1		
44		200	63.4	300	44.5	200	63.4	300	44.5	200	63.4		
45		250	62	400	23.5	250	62	400	23.5	250	62		
46		300	64.7	500	6.8	300	64.7	500	6.8	300	64.7		
47		350	69.3	600	0	350	69.3	600	0	350	69.3		
48		400	66.5			400	66.5			400	66.5		
49		450	48.8			450	48.8			450	48.8		
50		500	36			500	36			500	36		
51		550	30			550	30			550	30		
52		600	20.6			600	20.6			600	20.6		
53		650	11.9			650	11.9			650	11.9		
54		700	4.9			700	4.9			700	4.9		
55		800	0			800	0			800	0		
56													
57													

FIGURE 7.2 Topography Input: extract from Worksheet "Topography input"

	A	B	C	D	E	F	G	H	I
1	30/4/05 18:59								
2				TARGET SITE:					
3				MEAN WIND SPEED and GUST SPEED (if calculated) in m/s					
4									
5		Case:	1	2	3	4	5	6	7
6		Wind direction (deg from N):	225	225	270				
7		**Mean wind speed**	V_z (m/s)						
8		Height above ground (m)							
9		3	28.9	31.2	26.2				
10		5	31.3	33.6	28.7				
11		10	34.3	36.3	31.0				
12		20	37.3	39.0	33.3				
13		30	38.8	40.2	34.4				
14		40	39.9	41.2	35.3				
15		50	40.7	41.9	35.7				
16		65	41.6	42.5	36.1				
17									
18		**Gust speed**	V_{gz} (m/s)						
19		Gust averaging time, t(s)	3.00	3.00	3.00				
20		Height above ground (m)							
21		3	43.5	45.4	40.7				
22		5	46.0	47.0	42.5				
23		10	47.4	49.1	43.3				
24		20	51.8	52.5	47.0				
25		30	53.9	54.0	49.0				
26		40	55.4	55.4	50.4				
27		50	56.3	56.3	51.2				
28		65	57.0	57.2	51.7				
29									
30		If hilly, do calcs indicate that	Yes	Yes	Yes				
31		separated flow occurs?							
32									
33									
34		For any patches input as water, calculated values of z_0 (m) are:							
35		(starting with patch nearest site)							
36			0.00357	0.00378	0.00223				
37			0.00378		0.00311				
38									

FIGURE 7.3 Output Of Calculated Results: extract from Worksheet "Wind speeds"

The results in Figure 7.3 show that separated flow is likely to occur but Figure 7.4 shows that this region is not very close to the site so that it will not significantly affect the results.

In both directions, the shielding effect of the land on the sea surface is apparent from the smaller values of the surface roughness parameter, z_0, in the Figure 7.3 where z_0 for the inner region of water is less than the outer region of open sea.

In this example, the effect of non-uniform roughness in the terrain patches across the wind direction is significant, as shown by the difference in results between Case 1 and Case 2.

In this example, only wind speeds were calculated; if other calculation options on Worksheet "Target site" were selected, turbulence properties would appear in other output Worksheets.

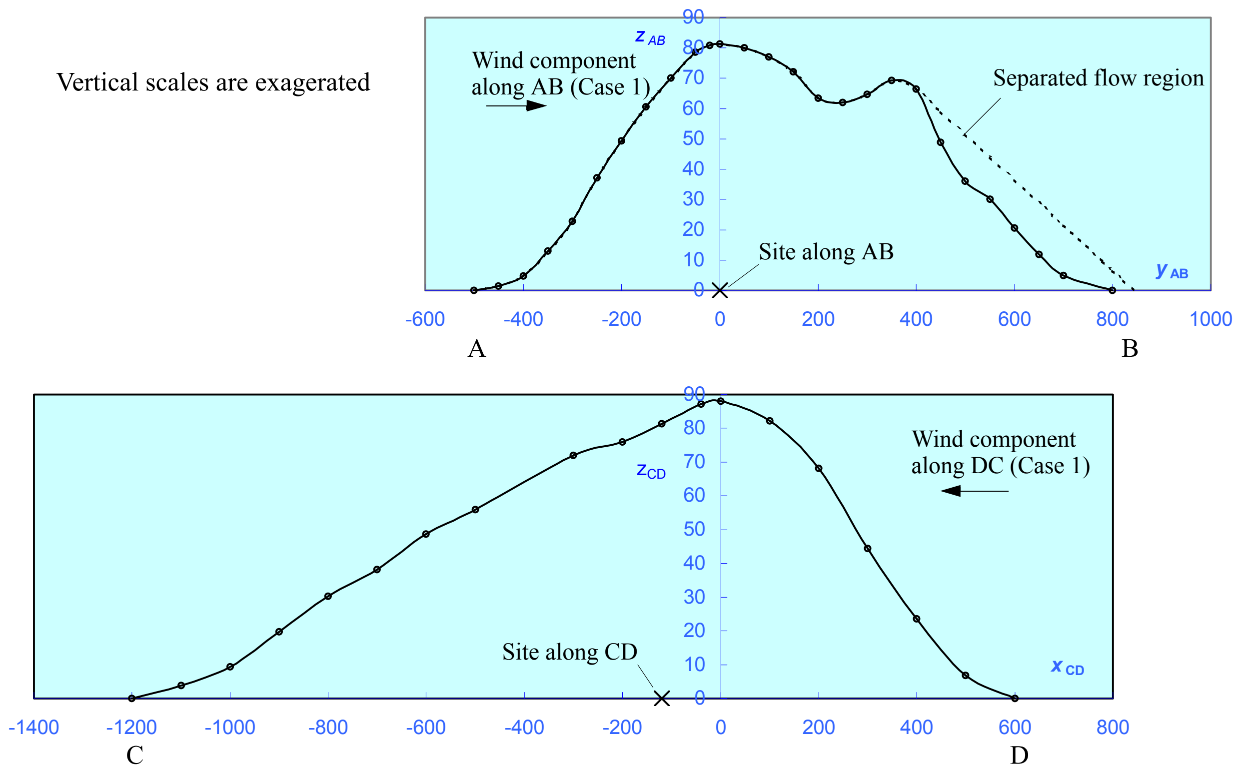


FIGURE 7.4 Cross-section Data for Example from Worksheet "Target site topography"

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9. COMPARISONS WITH MEASURED DATA FOR HILLY SITES

Two particular isolated hills have been chosen to compare full-scale measurements with results generated by the present method. These are the Askervein hill, located on the island of South Uist in the Outer Hebrides of Scotland, and Kettles Hill, in the Rocky Mountains of Western Canada. The full-scale measurement programmes were extensive and took place over several years; they were also backed up by wind-tunnel simulations.

Kettles Hill is generally elliptical in planform with an aspect ratio of about two. Askervein is larger than Kettles Hill and significantly steeper with regions of separated flow occuring; field experiments were carried out as part of an international project.

General descriptions of these projects and the principal measurements are given in Reference 8 (for Kettles Hill) and Reference 16 (for Askervein).

9.1 Comparison with Askervein Data

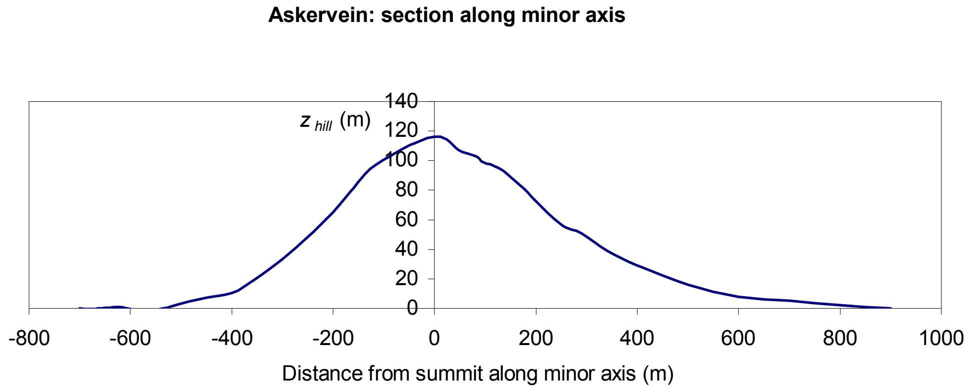
The principal full-scale measurements of speed-up factors were carried out with the wind direction approximately normal to the major axis of the hill (about 245° from north). In this case the downwind slope is sufficiently steep to cause local flow separation in this region. The hill summit is about 116 m above the surrounding terrain (generally flat with $z_0 \approx 0.03$ m); the profile of the hill through the summit along the minor axis is shown in Figure 9.1.

Comparison of the full-scale measurements with data generated by the ESDU program for a height above ground of 10 m is shown in Figure 9.1. Two full-scale runs are shown which, between them, exhibit significant differences; this is due mainly to the existence of unstable separated flow on the leeward slope. However, the present method reproduces the essential features of the separated flow region and compares well with an average of the two full-scale runs. Note the significant difference in the calculated values when separated flow is assumed (incorrectly) not to occur.

9.2 Comparison with Kettles Hill Data

In this case the principal measurements of speed-up factors were obtained with the wind direction at an angle of about 25° to the major W-E axis of the hill (245° from north). Cross section profiles of the hill through the summit along the minor and major axes are shown in Figure 9.2. The hill is about 100 m high but is less steep than the Askervein hill and flow separation does not occur. The ground cover on and around the hill consists mainly of short grass, stubble and snow-covered soil (for the period of the measurements); for this terrain a value of z_0 of about 0.007 m is assumed.

Comparison of the full-scale measurements with the present method is shown in Figure 9.2 for $z = 10$ m. In this case, the full-scale measurements are an average of several runs and the calculated data compare favourably with these.



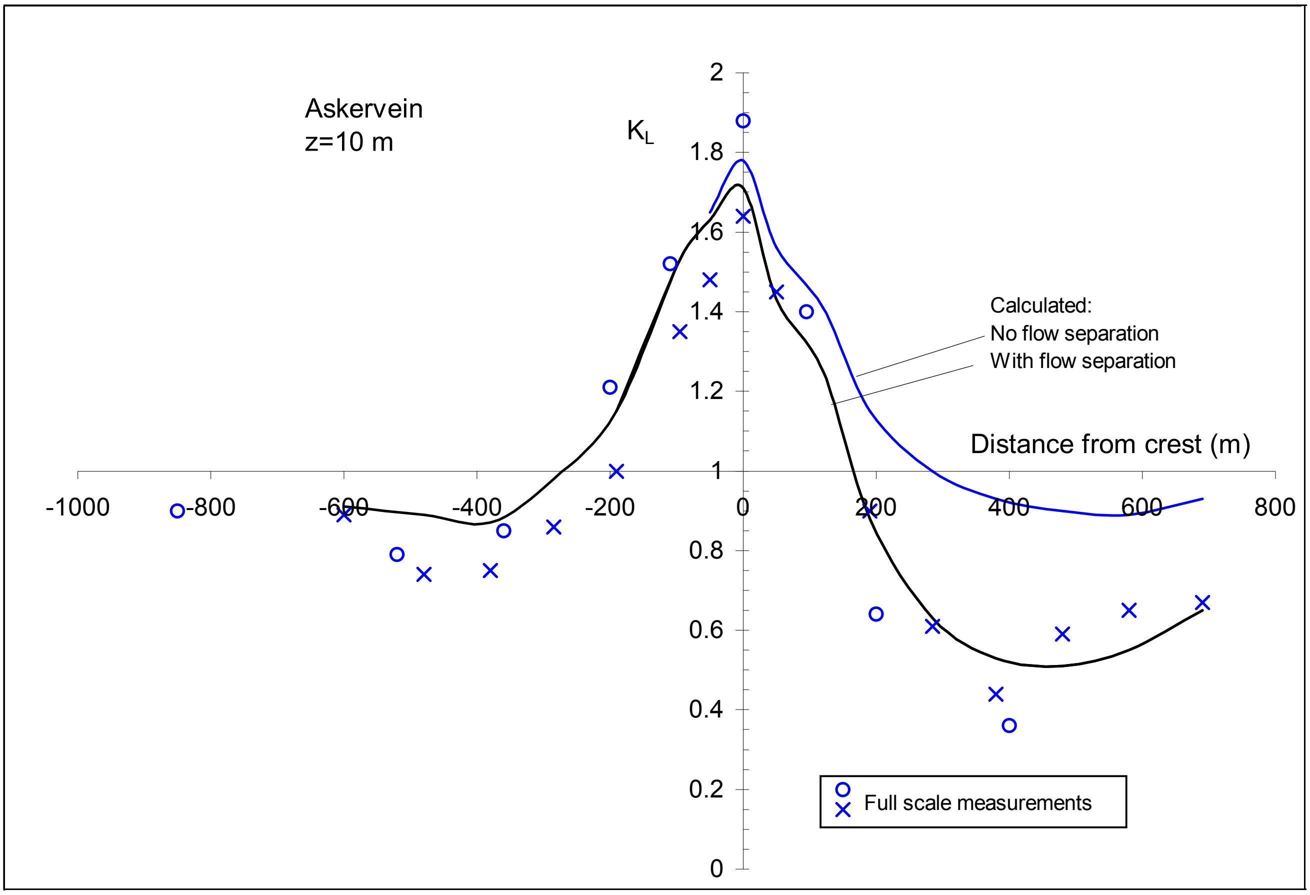
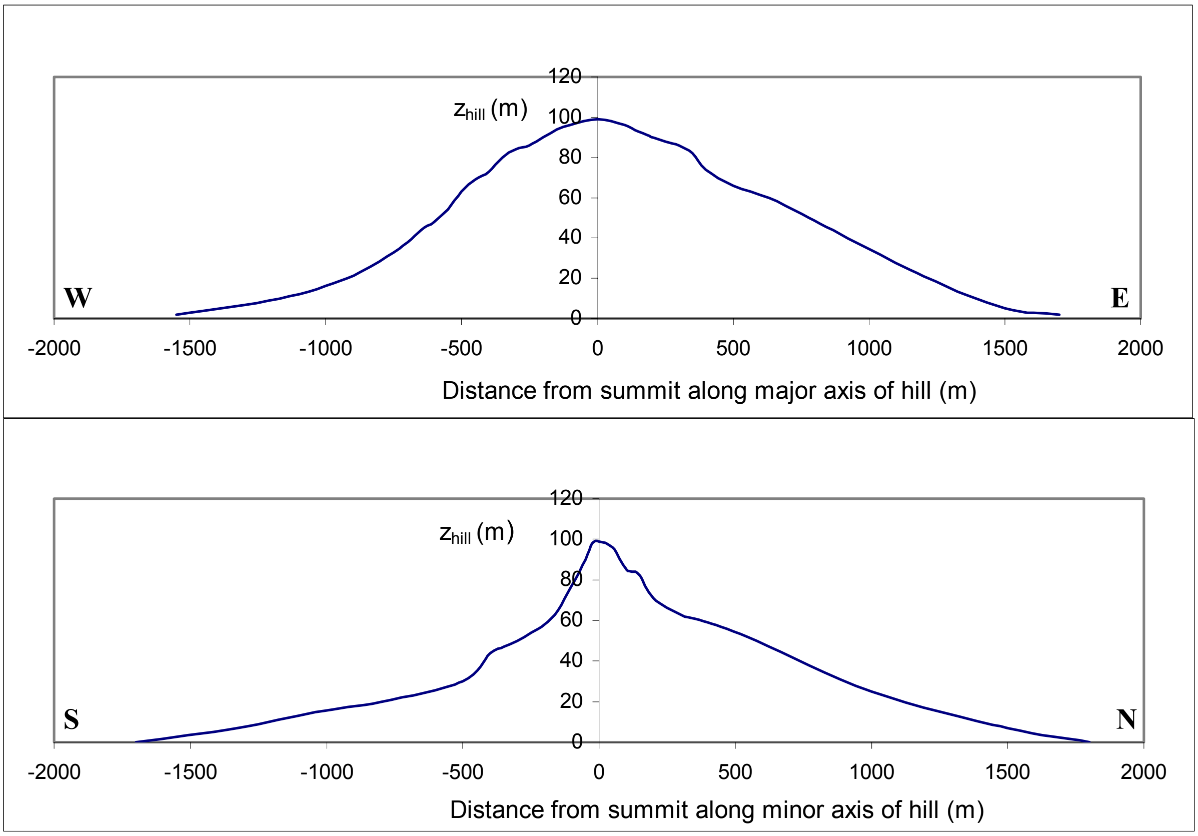


FIGURE 9.1 Data for Askervein: wind normal to minor axis of hill



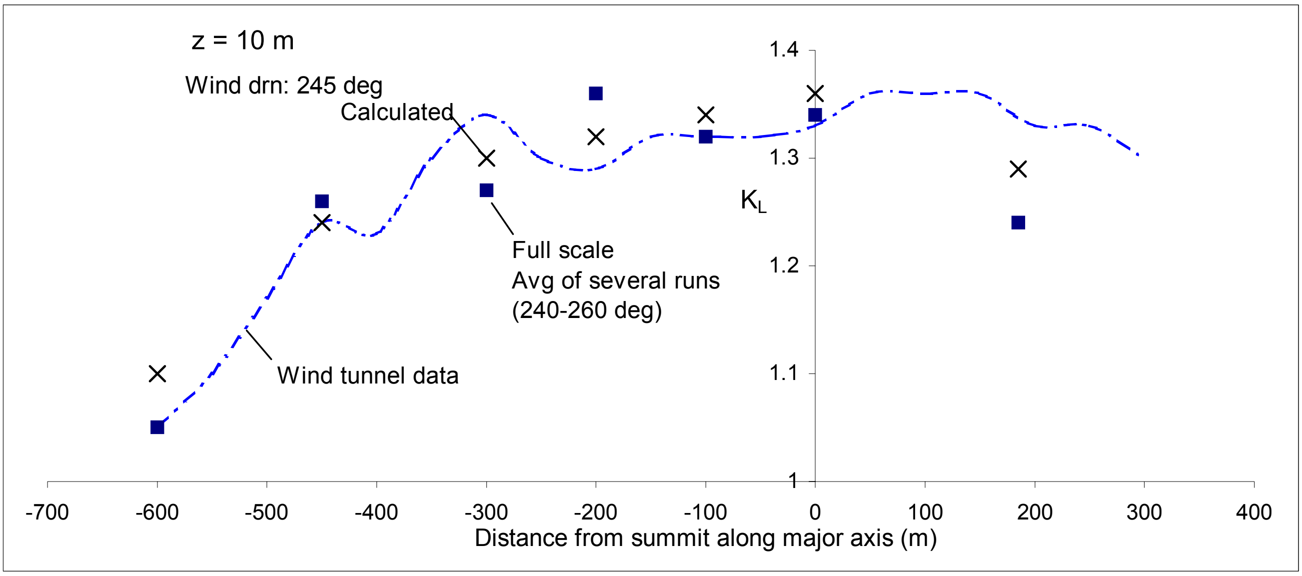


FIGURE 9.2 Data for Kettles Hill: wind direction 65° from S-N minor axis of hill

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01008

Computer program for wind speeds and turbulence properties: flat or hilly sites in terrain with roughness changes
ESDU 01008

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The purpose of ESDU 01008 is to provide detailed information on the use of, and background to, the Excel Visual Basic module E0108. This module, which runs in Excel 97 or later, can be used to estimate the variation of wind speed and turbulence properties with height in the atmospheric boundary layer. The module brings together the relevant methods for estimating the effects of terrain roughness changes, gust averaging time and topography (hills, valleys, *etc*.) described in other ESDU Data Items.

The spreadsheet presentation facilitates repeat runs with changes to the input. The facility is also available to reduce or correct measured wind properties (such as those from a local met. station) to values corresponding to standard conditions such as flat, uniform open country terrain, or to obtain corresponding values for some other terrain.

The program will calculate wind properties as a function of height over the site including hourly-mean wind speed and maximum gust speed, together with properties of the longitudinal (u) and lateral (v and w) components of turbulence (intensities, integral length scales and spectral densities). The program takes into account the following local conditions.

- Ground roughness at the site and variations in ground roughness upwind of the site including lateral variations in a terrain patch and the variation of sea-surface roughness with wind speed.

- Topographic effects on wind speed due to the location of the site in a hilly region, including ridges, embankments, escarpments or cliffs, or in a valley; topographic effects on turbulence properties for flow over hills with no flow separation.

A major feature of the program is its ability to deal with sites in complex terrain where the site is located within a range of hills. The general effect of topography is based on the two-dimensional computational method of Deaves but extended to include three-dimensional effects. The program incorporates a means of dealing with steep topography where flow separations occur and also a simplified model for estimating the distortion of spectra and turbulence variances over a hill.