



ESDU 86035

Issued December 1988
With Amendments A and E
April 1993
Re-issued February 2011

Integral length scales of turbulence over flat terrain with roughness changes

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THE PREPARATION OF THIS DATA ITEM

The work on this particular Data Item 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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INTEGRAL LENGTH SCALES OF TURBULENCE OVER FLAT TERRAIN WITH ROUGHNESS CHANGES

CONTENTS

	Page
1. NOTATION AND UNITS	1
1.1 Conversion Factors	1
2. PURPOSE AND SCOPE OF THIS DATA ITEM	2
2.1 Applicability of the Data	2
3. INTEGRAL LENGTH SCALES OF TURBULENCE: BACKGROUND	2
3.1 Relationship of Other Length Scales to ^xL_u	4
4. TABLES	5
4.1 Terrain Roughness	5
4.2 Length Scales of Turbulence, ^xL_u	5
4.2.1 No roughness changes	6
4.2.2 Single roughness change	6
4.2.3 Two roughness changes	7
TABLE 4.1 SITE ROUGHNESS $z_0 = 0.7$ m; UPWIND ROUGHNESS $z_{01} = 0.03$ m	8
TABLE 4.2 SITE ROUGHNESS $z_0 = 0.7$ m; UPWIND ROUGHNESS $z_{01} = 0.01$ m	8
TABLE 4.3 SITE ROUGHNESS $z_0 = 0.7$ m; UPWIND ROUGHNESS $z_{01} = 0.003$ m	8
TABLE 4.4 SITE ROUGHNESS $z_0 = 0.3$ m; UPWIND ROUGHNESS $z_{01} = 0.03$ m	9
TABLE 4.5 SITE ROUGHNESS $z_0 = 0.3$ m; UPWIND ROUGHNESS $z_{01} = 0.01$ m	9
TABLE 4.6 SITE ROUGHNESS $z_0 = 0.3$ m; UPWIND ROUGHNESS $z_{01} = 0.003$ m	9
TABLE 4.7 SITE ROUGHNESS $z_0 = 0.1$ m; UPWIND ROUGHNESS $z_{01} = 0.03$ m	10
TABLE 4.8 SITE ROUGHNESS $z_0 = 0.1$ m; UPWIND ROUGHNESS $z_{01} = 0.01$ m	10
TABLE 4.9 SITE ROUGHNESS $z_0 = 0.1$ m; UPWIND ROUGHNESS $z_{01} = 0.003$ m	10
TABLE 4.10 SITE ROUGHNESS $z_0 = 0.03$ m; UPWIND ROUGHNESS $z_{01} = 0.01$ m	11
TABLE 4.11 SITE ROUGHNESS $z_0 = 0.03$ m; UPWIND ROUGHNESS $z_{01} = 0.003$ m	11
TABLE 4.12 SITE ROUGHNESS $z_0 = 0.01$ m; UPWIND ROUGHNESS $z_{001} = 0.03$ m	11
TABLE 4.13 SITE ROUGHNESS $z_0 = 0.01$ m; UPWIND ROUGHNESS $z_{01} = 0.003$ m	11

TABLE 4.14 SITE ROUGHNESS $z_0 = 0.003$ m; UPWIND ROUGHNESS $z_{01} = 0.03$ m	12
TABLE 4.15 SITE ROUGHNESS $z_0 = 0.003$ m; UPWIND ROUGHNESS $z_{01} = 0.01$ m	12
TABLE 4.16 SITE ROUGHNESS $z_0 = 0.001$ m; UPWIND ROUGHNESS $z_{01} = 0.03$ m	12
TABLE 4.17 SITE ROUGHNESS $z_0 = 0.001$ m; UPWIND ROUGHNESS $z_{01} = 0.01$ m	12
TABLE 4.18 SITE ROUGHNESS $z_0 = 0.7$ m; UPWIND $z_{01} = 0.3$ m AND $z_{02} = 0.03$ m	13
TABLE 4.19 SITE ROUGHNESS $z_0 = 0.7$ m; UPWIND $z_{01} = 0.3$ m AND $z_{02} = 0.003$ m	14
TABLE 4.20 SITE ROUGHNESS $z_0 = 0.3$ m; UPWIND $z_{01} = 0.03$ m AND $z_{02} = 0.003$ m	15
TABLE 4.21 SITE ROUGHNESS $z_0 = 0.03$ m; UPWIND $z_{01} = 0.3$ m AND $z_{02} = 0.03$ m	16
5. REFERENCES	17
FIGURE 1	18

INTEGRAL LENGTH SCALES OF TURBULENCE OVER FLAT TERRAIN WITH ROUGHNESS CHANGES

1. NOTATION AND UNITS

		Units SI
k_L	factor accounting for variation of $[^xL_u]_x$ with V_{10r} and f	
d	height above ground of effective zero-plane to account for height and density of ground obstacles in built-up or wooded area (see Section 4)	m
f	Coriolis parameter, $f = 1.458 \times 10^{-4} \sin \phi$	rad/s
h	atmospheric boundary-layer height (see Equation (3.11))	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 or w components of turbulence along, x, y or z axes with x -axis in wind direction and z -axis vertical	m
$[^xL_u]_x$	local value of ^xL_u for non-equilibrium conditions at site	m
V_{10r}	reference, or basic, hourly-mean wind speed corresponding to a height of 10 m above flat, uniform open country terrain ($z_0 = 0.03$ m)	m/s
x, x_1, x_2	distance (fetch) over which uniform terrain roughness extends upwind of site and upwind of first and second upwind changes in terrain roughness	m
z	height measured from effective zero-plane (height above ground = $z + d$)	m
z_0, z_{01}, z_{02}	terrain roughness parameter (see Section 4) corresponding to fetches x, x_1, x_2	m
ϕ	angle of latitude at site	deg
Subscripts		
j	relates to value upwind of j th roughness change from site	
x	denotes local value at site when roughness changes exist upwind (non-equilibrium conditions)	

1.1 Conversion Factors

To convert m to ft multiply by 3.281

To convert m/s to mile/hr multiply by 2.237

Issued December 1986
With Amendments A to E, April 1993
Re-issued February 2011

2. PURPOSE AND SCOPE OF THIS DATA ITEM

Values of the characteristic properties of atmospheric turbulence, such as intensity and integral length scales of turbulence, are required in the evaluation of the fluctuating loading induced in a structure by turbulence in the wind. Within the atmospheric boundary layer these properties are controlled by the nature of the underlying terrain and also by the strength of the wind. Items 84011 and 84030 provide tables of wind speed factors and turbulence intensity values for various terrains with or without ground roughness changes upwind of the site.

The purpose of this Item is to provide a complementary set of Tables giving the longitudinal integral length scales of the u -component of turbulence, ^xL_u , (to which all other length scales can be related). The Index Tables in Section 4 indicate the range of terrain conditions for which data are presented and these include situations where roughness changes occur upwind of a site. The dependency of length scales on wind speed is important and so a simple correction factor is included for use with the tabulated data which are applicable for a reference wind speed, V_{10r} , of 20 m/s.

The equations for evaluating length scales of turbulence over terrain with roughness changes are detailed in ESDU 85020¹ (with Amendment E). The data in this Item have been generated using those equations.

The listing of a computer program to calculate local values of all integral length scales (and other wind speed and turbulence properties) is given in ESDU 01008³ for flat or hilly sites in terrain with multiple roughness changes. The relationships between length scales are given in Section 3.1.

2.1 Applicability of the Data

The method by which the data in the Tables have been derived is likely to be most reliable for situations involving adjacent changes in terrain roughness where $(z_0)_{\text{larger}}/(z_0)_{\text{smaller}}$ is less than about 10. The method and tabulated data are also likely to be increasingly unreliable as the number of upwind roughness changes increases.

3. INTEGRAL LENGTH SCALES OF TURBULENCE: BACKGROUND

Integral length scales of turbulence are a comparative measure of the “average size” of a gust in appropriate directions and they are important scaling factors in determining how rapidly gust properties vary in time and space. ESDU 85020¹ provides data giving the properties of atmospheric turbulence at individual points in space and ESDU 86010² describes the spatial variation of these properties between pairs of points.

The longitudinal length scale of the u -component of turbulence, ^xL_u , is particularly important since it is essential in determining the magnitude of the dynamic component of wind loading through the spectral density function, S_{uu} . Furthermore, all other lengths scales* can be related to ^xL_u as described in ESDU 86010² so that once ^xL_u is known, the remaining length scales can be determined. For convenience, these relationships are summarised in Section 3.1.

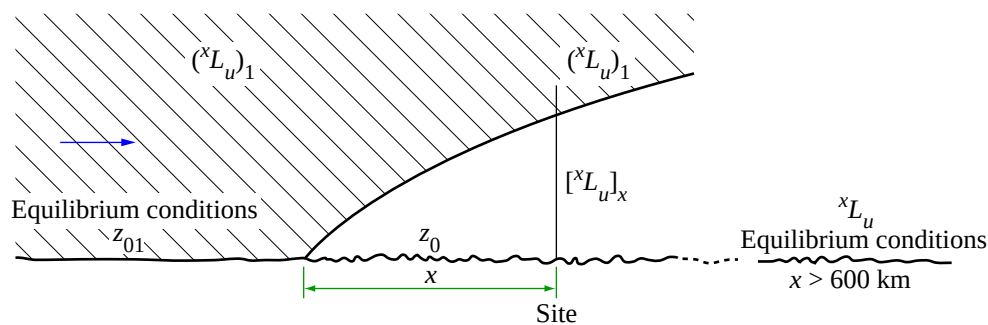
The main parameters that determine ^xL_u are

- (i) height above the ground.
- (ii) terrain roughness,
- (iii) wind strength (V_{10r}).

* There are nine principal length scales in all, three for each fluctuating wind-speed component u , v and w in each of the three orthogonal directions x , y and z .

Length scales increase with increasing height above the ground up to an asymptotic value at the edge of the atmospheric boundary layer (gradient height). Also, for a given height within the boundary layer they increase with increasing wind speed and surface roughness. The reason for this is that as wind strength increases the boundary layer height increases and eddies within the boundary layer are stretched accordingly. However, as explained in Section 7.1 of Reference 1, within an inner layer close to the ground (varying from several meters to several tens of meters as terrain roughness increases) length scales are dependent primarily on the degree of surface roughness (z_0); for a fixed height they will decrease with increasing z_0 but are essentially independent of wind speed.

In addition to the foregoing effects, a variation of terrain roughness upwind of the site gives rise to “non-equilibrium” conditions (when wind speed and turbulence properties are changing along the wind direction) with the following consequences.



Sketch 3.1

For a roughness change as illustrated in Sketch 3.1 where $z_{01} < z_0$, the value of $[xL_u]_x$ at the site will be considerably less than xL_u estimated assuming equilibrium conditions exist there (i.e. that x is ideally greater than about 600 km). In the same context the local hourly-mean wind speed and the local component of fluctuating wind speed (σ_u) are, respectively, greater than, and smaller than, the corresponding values assuming equilibrium conditions exist at the site.

For a roughness change where $z_{01} > z_0$ the opposite trend occurs.

When more than one roughness change takes place upwind of the site the situation becomes even more complex. Appendix A of ESDU 85020 explains how the case where multiple roughness changes occur upwind of the site may be treated. However, most practical situations can be simplified so that no more than two roughness changes need be considered.

The complexity of the interrelationships given in ESDU 85020 means that hand calculation of local values of length scale is time consuming. The Tables presented in Section 4, together with Equations (4.1) and (4.2) giving the effect of wind strength and $f \neq 1 \times 10^{-4}$ rad/s, are aimed at providing a quick guide to values of $[xL_u]_x$ that are representative of typical terrain conditions. It is important to appreciate that the simple graphical presentation for xL_u given in Figure 3 of ESDU 85020 applies only for equilibrium conditions when, ideally, the site terrain extends uniformly upwind for at least 50 km. It is rare that such conditions exist in practice; the equilibrium values of xL_u given in Figures 3a and 3b of ESDU 85020 are unlikely to apply except on the coast for off-sea winds or for large expanses of open country. The appropriate Table in Section 4 (or the computer program in ESDU 01008³) will provide more realistic values.

3.1 Relationship of Other Length Scales to ^xL_u

ESDU 86010 gives the following expressions for the ratio, $^rL_i / ^xL_u$ ($i = u, v$ or w ; $r = x, y$ or z) over uniform terrain. It may be assumed that the same relationships apply for non-uniform terrain with roughness changes.

$$2^yL_u / ^xL_u = 1.0 - 0.46 \exp [-35(z/h)^{1.7}] \quad (3.1)$$

$$2^zL_u / ^xL_u = 1.0 - 0.68 \exp [-35(z/h)^{1.7}] \quad (3.2)$$

$$2^xL_v / ^xL_u = (\sigma_v / \sigma_u)^3 \quad (3.3)$$

$$^yL_v / ^xL_u = (2^yL_u / ^xL_u)(\sigma_v / \sigma_u)^3 \quad (3.4)$$

$$2^zL_v / ^xL_u = (2^zL_u / ^xL_u)(\sigma_v / \sigma_u)^3 \quad (3.5)$$

$$2^xL_w / ^xL_u = (\sigma_w / \sigma_u)^3 \quad (3.6)$$

$$2^yL_w / ^xL_u = (2^yL_u / ^xL_u)(\sigma_w / \sigma_u)^3 \quad (3.7)$$

$$^zL_w / ^xL_u = (2^zL_u / ^xL_u)(\sigma_w / \sigma_u)^3. \quad (3.8)$$

The ratio of the standard deviations of the fluctuating velocity components, σ_v / σ_u , and σ_w / σ_u , are given by

$$\sigma_v / \sigma_u = 1 - 0.22 \cos^4 [(\pi/2)(z/h)] , \quad (3.9)$$

$$\sigma_w / \sigma_u = 1 - 0.45 \cos^4 [(\pi/2)(z/h)] . \quad (3.10)$$

For the purpose of using the preceding equations up to about $z = 300$ m, a sufficient approximation for h is given by

$$h \approx \frac{1700 V_{10r}}{\ln(10^5 / z_{0j})} \quad (3.11)$$

with h in metres for V_{10r} in m/s and z_{0j} (the upwind equilibrium terrain roughness) in metres.