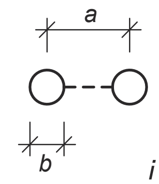
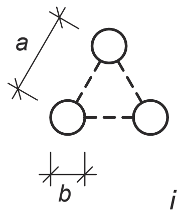
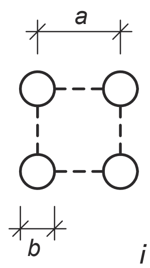
**A.2.3.3** It should be ensured that:

$$v_{CG} > 1{,}25 v_m(z) \quad \text{A.25}$$

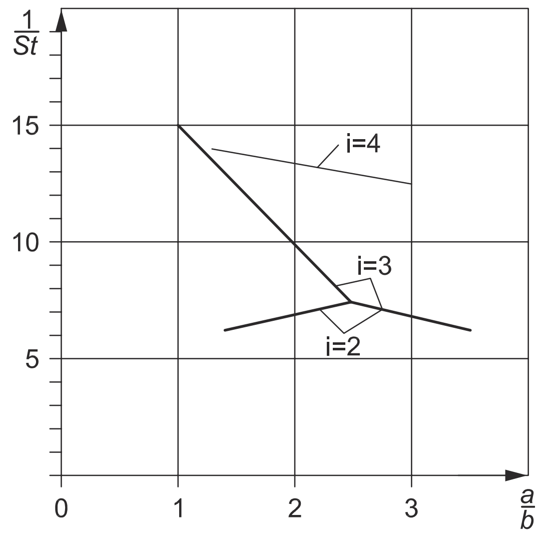
where:

$v_m(z)$ is the mean wind velocity as defined in Equation 4.3 of BS EN 1991-1-4:2005, calculated at the height $z$, where the galloping excitation is expected, that is likely to be the point of maximum amplitude of oscillation.

Table A.9 **Data for the estimation of crosswind response of coupled cylinders at in-line and grouped arrangements**

| | **Scruton number** $Sc = \frac{2\delta_s \sum m_{i,y}}{\rho b^2}$ (compare with Equation A.4) | | | |
|---|---|---|---|---|
| **Coupled cylinders** | $a/b = 1$ | $a/b \geqslant 2$ | $a/b \leqslant 1{,}5$ | $a/b \geqslant 2{,}5$ |
|   $i = 2$ | $K_{iv} = 1{,}5$ | $K_{iv} = 1{,}5$ | $a_G = 1{,}5$ | $a_G = 3{,}0$ |
|   $i = 3$ | $K_{iv} = 4{,}8$ | $K_{iv} = 3{,}0$ | $a_G = 6{,}0$ | $a_G = 3{,}0$ |
|   $i = 4$ | $K_{iv} = 4{,}8$ | $K_{iv} = 3{,}0$ | $a_G = 1{,}0$ | $a_G = 2{,}0$ |

**Linear interpolation**




Reciprocal Strouhal numbers of coupled cylinders with in-line and grouped arrangements

### A.2.4 Galloping, and stall flutter, for bridge decks

#### A.2.4.1 Calculation of onset wind velocity

*a) Vertical motion*

Vertical motion need be considered only for bridges of types 3, 3A, 4 and 4A as shown in Figure A.3, and only if $b < 4d_4$.

Provided constraints a), b) and c) in **A.1.5.4.2** are satisfied $v_g$ should be calculated from the reduced velocity $v_{Rg}$ using Equation A.26:

$$v_g = v_{Rg} n_{b1} d_4 \tag{A.26}$$

where:

$$v_{Rg} = \frac{C_g(m\delta_s)}{\rho {d_4}^2}$$

where:

$n_{b1}$ is the natural fundamental frequency (in Hz) in bending as defined in **A.1.3.1**;

$m$ and $\rho$ are as defined in **A.1.5.4.3**;

$C_g$ is 2,0 for bridges of type 3 and type 4 with side overhang greater than 0,7$d_4$ or 1,0 for bridges of type 3, 3A, 4 and 4A with side overhang less than or equal to 0,7$d_4$;

$\delta_s$ is the logarithmic decrement of damping, as specified in Annex F of BS EN 1991-1-4:2005;

$d_4$ is the reference depth of the bridge shown in Figure A.3, as defined in **A.1.3.2**.

Alternatively, wind tunnel tests should be undertaken to determine the value of $v_g$.

*b) Torsional motion*

Torsional motion should be considered for all bridge types. Provided the fascia beams and parapets conform to the constraints given in **A.1.5.4.2**, then $v_g$ should be taken as:

$v_g = 3.3 n_{t1} b$ for bridge types 1, 1A, 2, 5 and 6; A.27

$v_g = 5 n_{t1} b$ for bridge types 3, 3A, 4 and 4A. A.28

For bridges of type 3, 3A, 4 and 4A (see Figure A.3) having $b < 4d_4$, $v_g$ should be taken as the lesser of 12 $n_{t1}d_4$ or 5$n_{t1}b$

where:

$n_{t1}$ is the natural fundamental frequency in torsion in Hz as defined in **A.1.3.1**;

$b$ is the total width of bridge;

$d_4$ is as given in Figure A.3.

#### A.2.4.2 Criteria to be satisfied

The bridge should be shown to be stable with respect to divergent amplitude response in wind storms up to wind speed $v_{WO}$, given by:

$$v_{WO} = K_{1U} K_{1A} v_m(z)\left(1 + 2I_v(z)\sqrt{B^2}\right) \tag{A.29}$$

where:

$K_{1U}$ is a factor to cover the uncertainty of prediction in this field; the default value of $K_{1U}$ is 1,1;

$K_{1A}$ is a coefficient selected to give an appropriate low probability of occurrence of these severe forms of oscillation; for locations in the UK, $K_{1A}$ = 1,25.

*NOTE A higher value is appropriate for other climatic regions, e.g. typically $K_{1A}$ = 1,4 for a tropical cyclone-prone location.*

$v_m(z)$ is the mean wind speed derived in accordance with BS EN 1991-1-4:2005, **4.3.1**;

$I_v(z)$ is the turbulence intensity obtained from of NA to BS EN 1991-1-4:2005, **NA.2.16**;

$B^2$ is the background factor defined in BS EN 1991-1-4:2005, **6.3.1**.

Where the values of $v_g$ or $v_f$ derived in accordance with **A.2.4.1** or **A.4.4** respectively are lower than $v_{WO}$ further studies or wind-tunnel tests in accordance with **A.5** should be undertaken.

If the bridge cannot be assumed to be stable against galloping and stall flutter in accordance with the above criteria it should be demonstrated by means of a special investigation, or use of previous results, that the wind speed required to induce the onset of these instabilities is in excess of $v_{WO}$. It should be assumed that the structural damping available corresponds to the values of $\delta_s$ given in Annex F of BS EN 1991-1-4:2005.

## A.3 Interference galloping of two or more free standing cylinders

**A.3.1** Interference galloping is a self-excited oscillation which can occur if two or more cylinders are arranged close together without being connected with each other.

**A.3.2** If the angle of wind attack is in the range of the critical wind direction $\beta_k$ and if $a/b < 3$ (see Figure A.8), the critical wind velocity $v_{CIG}$ may be estimated by:

$$v_{CIG} = 3,5 n_{1,y} b \sqrt{\frac{\frac{a}{b} Sc}{a_{IG}}} \qquad \text{A.30}$$

where:

$Sc$ is the Scruton number as defined in **A.1.3.3**;

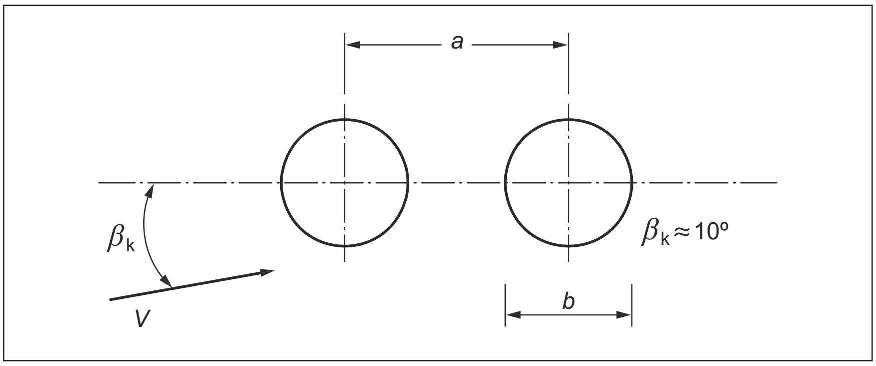
$a_{IG}$ is the combined stability parameter $a_{IG}$ = 3,0;

$n_{1,y}$ is the fundamental frequency of crosswind mode. Approximations are given in **F.2** of BS EN 1991-1-4:2005;

$a$ is the spacing;

$b$ is the diameter.

Figure A.8 **Geometric parameters for interference galloping**




**A.3.3** Interference galloping may be avoided by coupling the free-standing cylinders. In that case classical galloping can occur (see **A.2.3**).

## A.4 Divergence and Flutter

### A.4.1 General

Divergence and flutter are instabilities that occur for flexible plate-like structures, such as signboards or suspension-bridge decks, above a certain threshold or critical wind velocity. The instability is caused by the deflection of the structure modifying the aerodynamics to alter the loading.

Divergence and flutter should be avoided.

The procedures given in this subclause provide a means of assessing the susceptibility of a structure in terms of simple structural criteria. If these criteria are not satisfied, specialist advice is recommended.

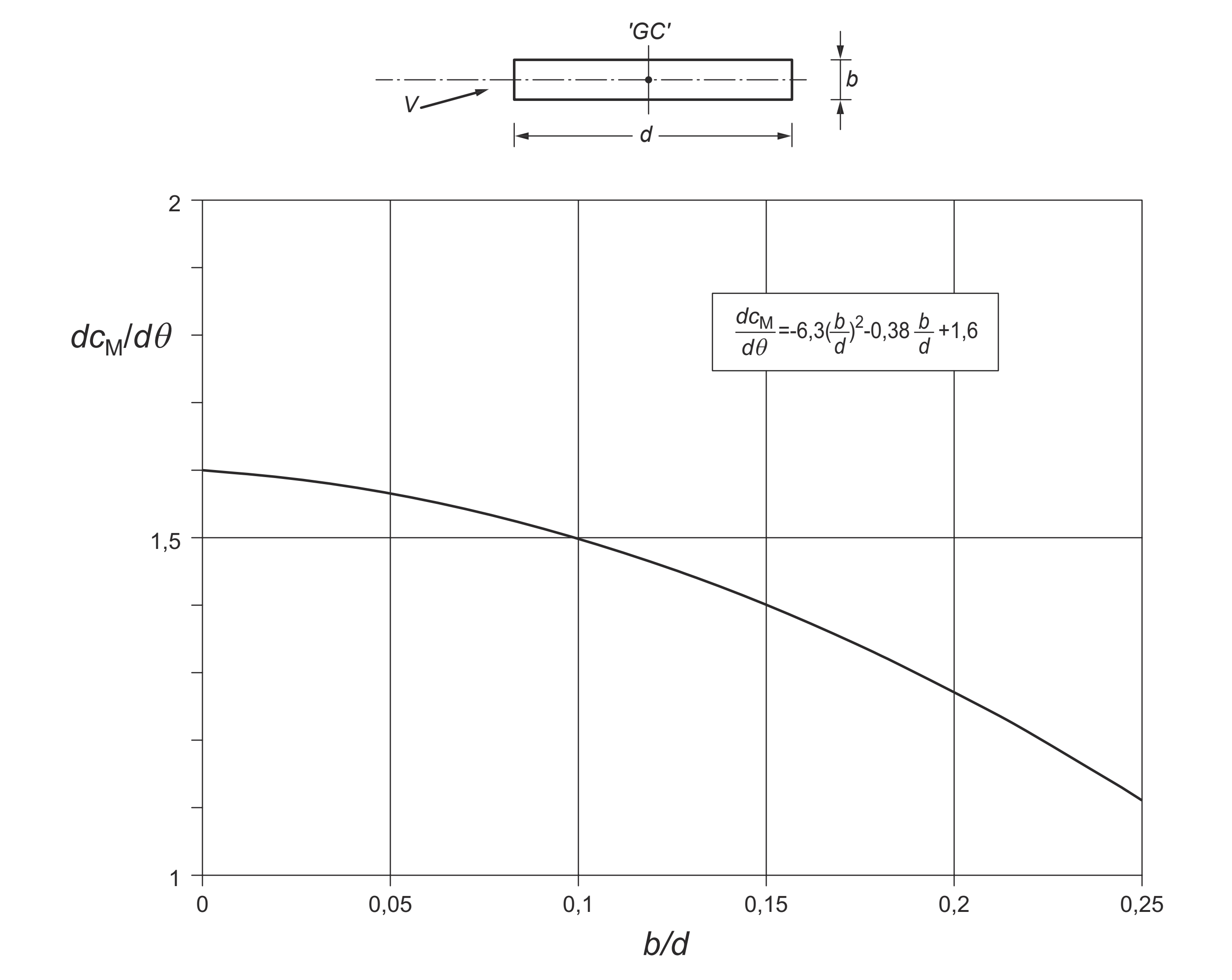
Subclause **A.4.2** provides criteria for plate-like structures and **A.4.3** a means of calculating the divergency velocity for such structures or elements. Subclause **A.4.4** provides criteria for bridge decks.

### A.4.2 Criteria for plate-like structures

To be prone to either divergence or flutter, the structure satisfies all of the three criteria given below. The criteria should be checked in the order given (easiest first) and if any one of the criteria is not met, the structure will not be prone to either divergence or flutter.

- The structure, or a substantial part of it, has an elongated cross-section (like a flat plate) with $b/d$ less than 0,25 (see Figure A.9).
- The torsional axis is parallel to the plane of the plate and normal to the wind direction, and the centre of torsion is at least $d/4$ downwind of the windward edge of the plate, where b is the inwind depth of the plate measured normal to the torsional axis. This includes the common cases of torsional centre at geometrical centre, i.e. centrally supported signboard or canopy, and torsional centre at downwind edge, i.e. cantilevered canopy.
- The lowest natural frequency corresponds to a torsional mode, or else the lowest torsional natural frequency is less than 2 times the lowest translational natural frequency.

Figure A.9 **Rate of change of aerodynamic moment coefficient $dc_M/d\theta$ with respect to geometric centre "GC" for rectangular section**




### A.4.3 Divergency velocity for plate-like structures

**A.4.3.1** The critical wind velocity for divergence is given in Equation A.31.

$$v_{\mathrm{div}} = \left[ \frac{2k_\theta}{\rho d^2 \frac{\mathrm{d}c_M}{\mathrm{d}\theta}} \right] \tag{A.31}$$

where:

$k_\theta$ is the torsional stiffness;

$c_M$ is the aerodynamic moment coefficient, given in Equation A.32:

$$c_M = \frac{M}{\frac{1}{2}\rho v^2 d^2} \tag{A.32}$$

$\mathrm{d}c_M/\mathrm{d}\theta$ is the rate of change of aerodynamic moment coefficient with respect to rotation about the torsional centre, $\theta$ expressed in radians;

$\rho$ is the density of air (see **A.1.5.4.3**);

$d$ is the in wind depth (chord) of the structure (see Figure A.7);

$b$ width as defined in Figure A.9.

**A.4.3.2** Values of $dc_M/d\theta$ measured about the geometric centre of various rectangular sections are given in Figure A.9.

**A.4.3.3** It should be ensured that:

$$v_{d/v} > 2v_m(z_e) \qquad \text{A.34}$$

where:

$v_m(z_e)$ is the mean wind velocity as defined in Equation 4.3 of BS EN 1991-1-4:2005 at height $z_e$ (defined in Figure 6.1 of BS EN 1991-1-4:2005).

## A.4.4 Flutter of bridge decks

### A.4.4.1 Calculation of onset velocity

The critical wind speed for classical flutter $v_f$ should be calculated from the reduced critical wind speed:

$$v_{Rf} = \frac{v_f}{n_{t1}b} \qquad \text{A.34}$$

i.e. $v_f = v_{Rf}n_{t1}b$, where:

$$v_{Rf} = 1{,}8\left[1 - 1{,}1\left(\frac{n_{b1}}{n_{t1}}\right)^2\right]^{1/2}\left(\frac{mr}{\rho b^3}\right)^{1/2} \text{ but not less than 2,5;}$$

$n_{t1}$, $n_{b1}$ are the predicted fundamental frequencies in torsion and bending (in Hz);

$m$, $\rho$ and $b$ are defined in **A.1.5.4.3**;

$r$ is as defined in **A.1.5.4.3**.

Alternatively the value $v_f$ may be determined by wind tunnel tests (see **A.5**).

### A.4.4.2 Criteria to be satisfied

The bridge should be shown to be stable with respect to flutter up to wind speed $v_{WO}$ given by Equation A.29.

If the bridge cannot be assumed to be stable against classical flutter in accordance with Equation A.34 it should be demonstrated by appropriate wind tunnel tests on suitable scaled models (see **A.5**) (or use of previous results), that the critical wind speed $v_f$ for classical flutter is greater than $v_{WO}$ (see **A.2.4.2**).

## A.5 Wind tunnel testing of bridges

Where a design is subject to wind tunnel testing, the models should accurately simulate the external cross-sectional details including non-structural fittings, e.g. parapets, and should be provided with a representative range of natural frequencies, mass, stiffness parameters and damping appropriate to the various predicted modes of vibration of the bridge.

Due consideration should be given to the influence of turbulence and to the effect of wind inclined to the horizontal, both appropriate to the site of the bridge. Tests in laminar flow may, however, be taken as providing conservative estimates of critical wind speeds and amplitudes caused by vortex shedding.

Where stability with respect to divergent amplitude response is established by section-model testing stability should be demonstrated up to the wind speed criterion $v_{WO}$ (see **A.2.4.2**) given by:

$$v_{WO} = K_{1U} K_{1A} v_m(z)\left(1 + 2I_v(z)\sqrt{B^2}\right) \qquad \text{A.35}$$

where:

$I_v(z)$ is the turbulence intensity obtained from **NA.2.16** of NA to BS EN 1991-1-4:2005;

$B^2$ is the background factor defined in BS EN 1991-1-4:2005, **6.3.1**.

This should be treated as a horizontal wind, or as inclined to the horizontal by an angle $\bar{\alpha}$ as a consequence of local topography. Although this occurs rarely for most locations in the United Kingdom, in cases where there are extensive slopes of the ground in a direction perpendicular to the span which suggest a significant effect on inclination of the mean flow, a separate topographical assessment (which may include wind tunnel studies) should be made to determine $\bar{\alpha}$. Stability should also be demonstrated in wind inclined to the horizontal by an angle $\alpha$ (in degrees) with speed criterion $v_{w\alpha}$ given by:

$$v_{w\alpha} = K_{1U} K_{1A} v_m(z) \qquad \text{A.36}$$

where:

$\alpha = \bar{\alpha} \pm 25 I_v(z)\sqrt{B^2}$ ;

$K_{1U}$, $K_{1A}$ are given in **A.2.4.2**.

For full-model testing, the criterion should be wind speed $v_{WE}$ given by:

$$v_{WE} = K_{1U} K_{1A} v_m(z)\left(1 + I_v(z)\sqrt{B^2}\right) \qquad \text{A.37}$$

Further guidance on wind tunnel testing is in preparation.

# Annex B (informative) Along-wind response of lattice towers

## B.1 General

This annex covers the along-wind gust buffeting response of freestanding lattice towers to enable BS EN 1993-3-1:2006, Annex B to be used with the UK National Annex (NA) to BS EN 1991-1-4.

The wind model in BS EN 1991-1-4 adopts five discrete terrain categories and assumes that wind speed and turbulence intensity profiles at a particular site are in equilibrium with the surrounding terrain. The NA to BS EN 1991-1-4 substitutes a transitional model where the wind speed and turbulence intensity profiles at a particular site are a function of the length and roughness of the upwind fetch and the height above ground level.

The method of calculation for along-wind gust buffeting response of freestanding towers given in BS EN 1993-3-1:2006, Annex B is compatible with the wind model in BS EN 1991-1-4. However, it is incompatible with the wind model in the NA to BS EN 1991-1-4; this annex provides a method of calculation to resolve this incompatibility.

## B.2 Codification

The following substitutions for codification are made from BS EN 1993-3-1:

In BS EN 1993-3-1:2006, equation B14a):

$$F_{m,W}(z) = q_m \sum c_f A_{ref} \qquad \text{B.1}$$

where:

$$q_m = 0.613 v_m^2 \qquad \text{B.2}$$

and:

$$v_m = c_r(z) c_{r,T}(z) c_o(z) v_b \qquad \text{B.3}$$

with $c_r(z)$ obtained from the NA to BS EN 1991-1-4:2005, Figure NA.3 and $c_{r,T}(z)$ obtained from the NA to BS EN 1991-1-4:2005, Figure NA.4; $c_o(z)$ is the orography factor.

Thus, the proposed method in this Annex B uses the wind speed and turbulence profiles presented in the NA to BS EN 1991-1-4.

In BS EN 1993-3-1:2006, equations B.14b), B.15 and B.17:

$$\{[1+7I_v(z_e)]c_s c_d - 1\} = G_{EN} \qquad \text{B.4}$$

This annex gives the following modified equations:

$$F_{T,W}(z) = F_{m,W}(z) \left\{1 + \left[1 + 0{,}2\left(\frac{z_m}{h}\right)^2\right] G_{EN}\right\} \qquad \text{B.5}$$

[BS EN 1993-3-1:2006, equation B.14b)]

$$S_{max}(z) = S_{m,W}(z) \left\{1 + \left[1 + 0{,}2\left(\frac{z_m}{h}\right)^2\right] G_{EN}\right\} \qquad \text{B.6}$$

(BS EN 1993-3-1:2006, equation B.15)

$$S_{1,TW}(z) = S_{m,TW}(z) \left[1 + 0{,}2\left(\frac{z_m}{h}\right)^2\right] G_{EN} \qquad \text{B.7}$$

(BS EN 1993-3-1:2006, equation B.17)

*NOTE These modified equations also remove the orography factor [$c_o(z_m)$] from the definition of $G_{EN}$. This is because orography accelerates the mean flow but not the turbulent part. This is accounted for correctly in BS EN 1991-1-4 and its NA, so further adjustment is not required within the definition of $G_{EN}$.*

## B.3 Methodology

The gust factor $G_{EN}$ is defined as follows:

$$G_{EN} = (gf)(2J_a J_p I_{v,0}) \tag{B.8}$$

$J_a$ and $J_p$ are aerodynamic admittances, defined here for a particular height above ground level and tower of total height (H):

$$J_a{}^2 = \left( \frac{\int_z^H \gamma_z dz}{\int_z^H \gamma \frac{I_{v,ref}}{I_v(z)} dz} \right)^2 \tag{B.9}$$

and:

$$J_p{}^2 = \frac{\int_z^H \int_z^H \gamma_z \gamma_{z'} C(z-z')dzdz'}{(\int_z^H \gamma_z dz)^2} \tag{B.10}$$

where:

$I_v$ is the turbulence intensity

z, z′ are the distance above ground of any two points

$\gamma_z$ is the non-dimensional coefficient, calculated as:

$$\gamma_z = \frac{\overline{V}_z b_z \beta(z) \sigma_v(z)}{\overline{V}_o b_o \beta_o \sigma_o} \tag{B.11}$$

where:

$\overline{V}_z$ is the 10 min mean wind speed at height z, in m/s;

$b_z$ is the wind resistance at height z, in $m^2/m$;

$\beta_z$ is the structural influence factor at height z;

$\sigma_z$ is the turbulence at height z, in m/s.

Coefficients with a subscript of zero should be taken at the same arbitrary reference height.

The term C(z-z′) is defined as follows:

$$C(z-z') = \exp\left( \frac{-|z-z'|}{{}^zL_u} \right) \tag{B.12}$$

${}^zL_u$ is the length scale for the along-wind gust component (u) for vertical separation (z). It is shown in Table B.1 to Table B.7. Table B.1 should be used for sites in country terrain; Table B.2 to Table B.7 should be used for sites in town terrain. Intermediate values may be obtained by interpolation.

Values of length scale have been calculated using ESDU Data Item 86035 [13]. Values have been calculated for a basic hourly mean wind speed at 10 m above ground level in country terrain ($z_0$ = 0,03 m) of 23 m/s and a Coriolis factor of 11,8 × $10^{-5}$, which are typical values for the UK.

Table B.1 **Length scale $^zL_u$ for a single roughness change from sea to country terrain, for an upwind fetch from site to sea of x(km)**

| z (m) | 0,1 km | 0,3 km | 1 km | 3 km | 10 km | 30 km | >600 km |
|---|---|---|---|---|---|---|---|
| 10 | 16 | 14 | 13 | 13 | 14 | 15 | 17 |
| 15 | 25 | 22 | 20 | 20 | 21 | 22 | 25 |
| 20 | 33 | 29 | 27 | 26 | 27 | 28 | 32 |
| 30 | 44 | 38 | 36 | 36 | 36 | 38 | 43 |
| 40 | 50 | 45 | 42 | 43 | 44 | 45 | 51 |
| 50 | 53 | 50 | 46 | 48 | 50 | 52 | 57 |
| 60 | 56 | 54 | 50 | 52 | 56 | 57 | 63 |
| 70 | 59 | 58 | 53 | 55 | 61 | 64 | 69 |
| 80 | 62 | 62 | 57 | 59 | 66 | 70 | 75 |
| 90 | 66 | 66 | 61 | 62 | 70 | 77 | 81 |
| 100 | 69 | 69 | 65 | 65 | 75 | 83 | 87 |
| 120 | 77 | 77 | 74 | 72 | 84 | 96 | 100 |
| 140 | 85 | 85 | 83 | 80 | 92 | 109 | 114 |
| 160 | 93 | 93 | 92 | 87 | 100 | 121 | 127 |
| 180 | 101 | 101 | 100 | 94 | 107 | 133 | 141 |
| 200 | 108 | 108 | 108 | 102 | 114 | 143 | 154 |
| 250 | 126 | 126 | 126 | 122 | 127 | 165 | 185 |
| 300 | 141 | 141 | 141 | 139 | 138 | 179 | 213 |

Values of $^zL_u$ should be calculated at an elevation midway between the top of the tower (H) and the height of interest (z).

Figure B.1 **Gust peak factor (Davenport's g)**