WIND ACTIONS TO BS EN 1991-1-4

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WIND ACTIONS TO BS EN 1991-1-4

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A F Hughes MA MICE MIStructE

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FOREWORD

This guidance has been prepared to assist structural engineers with the evaluation of wind actions for buildings in the UK in accordance with the provisions of BS EN 1991-1-4[1] ('the Standard'), its UK National Annex[2] ('the NA') and the additional guidance contained in BSI Published Document PD 6688-1-4[3] ('the PD'). The focus is on the calculation of overall lateral wind forces acting on orthodox steel framed buildings. Evaluation of surface pressures is also covered. Little attention is given to material in the Standard, NA and PD which is of interest mainly to bridge, chimney or tower designers.

Wind action is an important design consideration for most buildings, and very important for some. Numerous influences, with directional variation, are factored into a wind calculation. Within the framework of BS EN 1991-1-4, designers have to strike a balance between simplicity, with conservative results, and more involvement, yielding more precision.

Since 2010, the Standard and NA in combination have provided the UK with a substantial technical advance on BS 6399-2[4]. However the challenges of harmonization, together with the rules governing the preparation of Eurocodes and their supporting documents, have had adverse effects on presentational coherence. The aim of the present Design Guide is to set out the procedure for UK wind calculations in an accessible and comprehensible manner.

The content was drafted by Alastair Hughes of the Steel Construction Institute, and reviewed by colleagues, notably David Iles, whose painstaking efforts to improve and prepare it for publication deserve special acknowledgement.

Particular thanks are due to Dr Paul Blackmore of BRE Group, John Rees of Flint & Neill and Prof R S Naryanan of Clark Smith Partnership for generous assistance with interpretation of Standard and NA provisions and for their scrutiny of the final draft. Helpful discussions with Andrew Allsop, David Brown and Brian Smith are also gratefully acknowledged. Dr Buick Davison of Sheffield University has kindly provided information for the design example.

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CONTENTS

SUMMARY

This publication has been prepared to guide structural engineers through the process of establishing design wind actions for orthodox steel framed buildings in the UK, in accordance with the Eurocodes, UK National Annexes and other authoritative information.

The calculation procedure to determine design wind actions is set out in Sections 5 and 6 and is demonstrated in a numerical example in Sections 9 and 10.

NOTATION

Where wind is concerned, the axis convention is that x is the wind direction and z is upwards.

The list which follows is not exhaustive but includes most of the symbols referred to in this Design Guide.

A	Altitude; area, e.g. face or shadow area; coefficient in polynomial expression for orographic location factor
B	Coefficient in polynomial expression for orographic location factor
b	Breadth (the cross-wind dimension for a building or element)
c	Coefficient; factor (see glossary below)
d	Depth (the in-wind dimension for a building or element); distance
e	Eccentricity; zone extent parameter ('scaling length', the smaller of b and $2h$)
F	Force
H	Height, e.g. of hill or cliff
h	Height, e.g. of building or displacement
I	Intensity of turbulence (expressed in velocity terms as $I_v = \sigma_v/v_m$)
L	Length, e.g. of slope
l	Length
n	Natural frequency
p	Annual probability of exceedance
q	Velocity pressure (= dynamic pressure = stagnation pressure)
r	Radius
s	Orographic location factor
v	Velocity
w	Wind pressure (relative to atmospheric)
X	Distance from orographic crest (negative upwind)
x	Coordinate in wind direction
y	Coordinate in cross-wind direction
z	Coordinate in vertical direction (height above ground)

α	Roof angle
γ	Partial factor
δ	Logarithmic decrement of damping
ζ	Critical damping ratio
θ	Wind direction (0° from North, 90° from East etc.)
λ	Slenderness
ρ	Density (of air; taken as 1.226 kg/m^3 in UK)
σ	Standard deviation
ϕ	Upwind slope (of orographic feature)
φ	Solidity ratio
ψ	Factor (commonly a reduction factor)

Subscripts

alt	altitude
ave	average ('av' in the PD)
b	basic
crit	critical
d	dynamic; design; downslope
dir	directional
dis	displacement
e	exposure; external; effective; equivalent; reference (in z_e)
e,T	correction for exposure in town
f	force
fr	friction
flat	flat; 'non-orographic'
i	internal
loc	lack-of-correlation
m	mean
map	from the wind map
net	combined effect of opposite sides
o; (o)	orography
p	peak; pressure; parapet
prob	probability
r	roughness (of terrain); rounded (corners)
r,T	correction for roughness in town
ref	reference

s	size; reference (in z_s)
sh	shadow (A_{sh} = projected area as viewed in wind direction)
shed	(A_{shed} = plan area of multispan roof; see EN 1991-1-4, 7.2.7(4))
sw	swept (A_{sw} = area of faces aligned with the wind)
T	town
u	upwind; upslope
v	velocity
w	wind
x	in-wind
y	cross-wind
z	vertical
0	basic (e.g. at 10 m above ground); for wind angle 0°; combination value; without free-end flow
1	fundamental (Mode 1) when applied to natural frequency n
α	inclinational
θ	rotational
λ	end effect

Glossary of c-factors and coefficients

SYMBOL	NAME	APPLIES TO:
c_{alt}	Altitude factor (≥ 1)	
c_{dir}	Directional factor (≤ 1)	
c_{season}	Season factor (≤ 1; = 1 for all normal buildings)	Velocity
c_{prob}	Probability factor (= 1 for all normal buildings)	
c_r	Roughness factor (see note 1 below)	
$c_{r,T}$	Town terrain roughness correction factor (≤ 1)	
c_o	Orography factor (> 1; ignorable if < 1.05)	See note 2 below
c_e	Exposure factor (see note 1 below)	
$c_{e,T}$	Town terrain exposure correction factor (≤ 1)	
c_s	Size factor (≤ 1)	
c_d	Dynamic factor (≥ 1)	
$c_s c_d$	'Structural' factor (see note 3 below)	
c_{pe}	External pressure coefficient	Pressure (or its effects)
c_{loc}	Lack-of-correlation factor ($0.85 \leq c_{loc} \leq 1$)	
c_{pi}	Internal pressure coefficient	
$c_{p,net}$	Net pressure coefficient	
c_f	Force coefficient	
c_{fr}	Friction coefficient (range 0.01 to 0.04)	

Note 1: Exposure factors and roughness factors are never used together. The simpler treatment (Section 5 of this Design Guide) uses exposure factors. c_r is not to be confused with the 'roughness factor' for a multispan roof introduced (without symbol) in EN 1991-1-4, 7.2.7(4).

Note 2: The orography factor c_o only applies directly, to **mean** velocity, with the more elaborate treatment (obligatory for buildings over 50 m in 'orographic' situations). In the simpler treatment, the factor which applies, to **peak** velocity, is $[(c_o + 0.6)/1.6]$.

Note 3: In the UK the recommended approach is to determine the c_s and c_d factors separately.

In EN 1991-1-4, the NA and the PD, (z) is sometimes appended to a symbol to indicate that the symbolized variable is for height above ground z. This practice may be regarded as optional and has not been adopted here. Thus, for instance, Expression (NA.4b), which appears in the NA as:

$$q_p(z) \qquad = [1 + 3{,}0 \cdot I_v(z)]^2 \cdot 0.5 \cdot \rho \cdot v_m{}^2$$

would be presented in this Design Guide, which adheres to standard UK practice in the use of decimal points, as:

$$q_p \qquad = 0.5\rho[v_m\,(1 + 3I_v)]^2$$

In several cases, expressions found in the Standard and the NA are rearranged in this Design Guide for simplicity and clarity.

INTRODUCTION

1.1 Design Standard and supporting documents

This publication provides guidance for designers using the Eurocodes for buildings in the UK. Comparison with BS 6399-2 is made sparingly, but due emphasis is given to unfamiliar methods and terminology.

The Eurocode for wind actions, EN 1991-1-4, is not intended to be used alone, even if all its Recommended Values (RVs) were accepted. Unlike EN 1991-1-3[5], which contains a set of European snow maps, EN 1991-1-4 does not include wind maps. Users are reliant on the relevant national annex to deliver information on the national wind climate and to set Nationally Determined Parameters (NDPs). The UK NA's intervention goes beyond the provision of climatic information. EN 1991-1-4 offers more than 60 formal opportunities for national choice to deviate from its recommendations, and national choice is much exercised by the UK. This is done in the interests of technical quality and simplicity, but at some cost to coherence of presentation.

For design of structures located in the national territory, NDPs in the national annex prevail over any RVs given in the Standard.

The latest version of the Standard at time of writing is EN 1991-1-4:2005+A1:2010. The UK NA referred to is 'National Amendment No 1' (dated 2010, issued January 2011) which incorporates significant amendments to the 2008 version, including a revised wind map and a full set of nationally determined pressure coefficients.

The Eurocode system, while permitting national choice (in specific instances where it is invited), does not allow national annexes to give reasons for those choices. PD 6688-1-4:2009 has been issued as a BSI 'Published Document' to explain and justify the choices made in the NA on behalf of UK building designers, owners and users. The PD has the status of 'Non-Contradictory Complementary Information' (NCCI). At time of writing, the PD had yet to be revised to reflect the 2010 changes.

Designers should note that PD 6688-1-4 contains 'additional guidance' similar in its presentation to normative material. This may be viewed as a way to retain valued BS 6399-2 provisions which are not incorporated in the European Standard.

In general, NCCI (of which the present publication is an example) can come from a variety of sources, not subject to official control. However, a BSI Published Document such as PD 6688-1-4 is NCCI at its most authoritative, albeit 'informative' not 'normative'.

BS EN 1991-1-4 is published by BSI as the English language version of EN 1991-1-4 (as published by CEN) together with a National Foreword (NF). The NF is purely explanatory and contains no technical provisions. The NA, although an integral part of the National Standard implementing the Eurocode, is published under separate cover, as is the PD. In this Design Guide, it is necessary to explain differences between the Eurocode and its UK implementation. To distinguish between them, the former is referred to as EN 1991-1-4 (or 'the Standard'), with the BS prefix reserved for the latter.

1.2 Scope

It would be unrealistic for the present Design Guide to stand alone as a replacement for the Eurocode, NA and PD. Its ambition is more limited: to allow peak velocity pressures and overall wind forces for most steel buildings in the UK to be calculated without constant reference to the official documents. At various stages, and for further detail, it will be necessary to have them to hand.

This Design Guide is for buildings in the UK. For a building located outside the UK, the relevant national annex is liable to impose quite different parameters and methodology.

The 'mainstream' procedure, set out in Section 5, is for orthodox steel framed buildings of height up to 100 m, **unless** they are in orographic situations (where the oncoming wind has been accelerated by a hill or cliff), in which case the height must not exceed 50 m. The reason for the latter limitation is that the simpler treatment of the NA, used in Section 5, becomes invalid. The more elaborate treatment, obligatory for buildings over 50 m high in orographic situations, is outlined in Appendix A. An introduction to orography and the terms used in this Design Guide is given in Section 2.4.

The advice in this Design Guide does not become invalid above 100 m, but dynamic performance increasingly demands consideration. Figure 1.1 gives an illustration of the applicability of this publication and that of the Standard. In the centre of the photograph, Citi Phase 1 (in its higher part) is just over 100 m. Behind, HSBC and Citi Phase 2, both 200 m, are at the limit of applicability of EN 1991-1-4. One Canada Square, partly visible at top left, is (at time of writing) one of three UK buildings which are outside the scope of the Standard.

Figure 1.1 Canary Wharf: Citi Phase 1 (foreground); HSBC and Citi Phase 2 (behind)

Bridges are outside the scope of this Design Guide, as are canopies, signboards, chimneys, tanks, towers and masts. Temporary buildings (and other buildings with an indicative design life different from the normal 50 years) are not covered in the procedure in Section 5, though EN 1991-1-4 does contain provision for ‘probability’ and ‘season’ factors to be applied in such circumstances. These factors, not of concern in normal building design, are discussed in Appendix B.

This Design Guide is essentially concerned with buildings in their final condition, but part-completed buildings can be more vulnerable to wind than the finished product. EN 1991-1-4, 2(3) is a reminder that design situations in course of execution may need to be considered.

Most of the content of this publication would apply equally to non-steel-framed buildings, but dynamic factors may vary.

1.3 Arrangement of this Design Guide

Sections 2, 3 and 4 contain background information aimed at readers new to the subject.

The core of the Design Guide, in Section 5, is a 25-stage procedure to determine the overall wind force on a building which qualifies, as most UK buildings will, for the simpler (exposure factor) treatment of the NA. Section 6 covers the evaluation of surface pressures.

EN 1991 delivers characteristic (unfactored) values of actions. Design values for ultimate limit state (ULS) design situations are the product of characteristic values and EN 1990[6] partial factors, whose impact is discussed in Section 7.

The circumstances in which specialist wind engineering advice can be advantageous are briefly reviewed in Section 8.

Section 9 provides a design example to demonstrate the procedure of Section 5; Section 10 illustrates surface pressure calculation, as described in Section 6.

Appendix A outlines the more elaborate (roughness factor) treatment, which must be followed if the building is over 50 m in height **and** in an ‘orographic’ situation. Appendix B deals with factors applicable in temporary and/or transient situations. Appendix C provides a blank worksheet for manual calculation and a ‘Wind Protractor’, which can be photocopied onto transparent film to facilitate directional calculations.

THE NATURE OF WIND

2.1 The wind climate

Figure 2.1
Cup Anemometer by Vector Instruments
Courtesy of Windspeed Ltd.

Wind arises from instabilities in the earth's atmosphere caused by rotation of the planet and surface temperature variations. The resulting air flow is influenced by mountains and by friction at the surface. Wind is a complex phenomenon in three dimensions (four, if time is included) and the science behind wind resistant design is essentially observational. In the UK, design values of wind speed are derived from statistical analysis of records from around 50 anemometer stations distributed throughout the British Isles. There is an implied assumption that the wind climate is unchanging.

2.2 The atmospheric boundary layer

Buildings occupy an atmospheric 'boundary layer', within which wind speed gradually increases with height. Above a somewhat ill-defined 'gradient height', mean wind velocity is more or less constant. The atmospheric boundary layer is analogous to the much-studied boundary layer of an aircraft wing, but on a vastly greater scale. The velocity near the surface, and the gradient (its rate of increase with height), depend on how much energy has been extracted by friction over the preceding terrain. Hence the importance of upstream terrain roughness. EN 1991-1-4 defines five terrain categories, but these are further simplified by NA.2.11 into three: Sea, Country and Town.

The boundary layer of an aircraft wing can be either laminar (smooth flow) or turbulent (confused flow, with a significant randomness to the direction of motion). In contrast, the atmospheric boundary layer is always a turbulent one, and the degree of turbulence is an important variable. Rough terrain upstream makes the flow more turbulent, as well as reducing mean velocity. Thermal effects are also instrumental in promoting turbulence, especially in towns. It takes some time, and some distance, for these effects to work upwards through the boundary layer. Graphs in Figures NA.7 and 8 (Figure 5.9 and Figure 5.11 of this Design Guide) give an indication of the rate at which the Zone A (maritime) boundary layer is supplanted by Zone B (rural) and in turn by Zone C (urban).

2.3 Turbulence

For structural and facade engineers, the importance of turbulence is that it superimposes peaks and troughs on the mean wind speed, and consequently increases the peak pressures to be designed against. Turbulence on the scale that a building will react to (upwards of about a metre in extent, or a second in duration) is more popularly described as gustiness, and is responsible for a significant component of the design action.

Figure 2.2 Boundary Layer Wind Tunnel

Courtesy of BMT Fluid Mechanics

Present design methods are founded on experiment, sometimes at full scale but more often in the laboratory. The technique of recreating a scaled atmospheric boundary layer in the wind tunnel is well developed. To be valid, wind tunnel tests must properly model the velocity gradient and turbulence at the building location, and this is emphasized in the guidance on testing in NA.2.2.1. Smooth flow experiments in aeronautical wind tunnels give unreliable results.

2.4 Orography

Wind is deflected, and thereby accelerated, when high ground is encountered. Major mountain ranges have a profound and global effect but the relatively modest landforms encountered in the UK are also influential, especially in the immediate vicinity of cliffs and other pronounced hills, ridges and escarpments. In this Design Guide, the term 'orographic' is used where these local effects are significant. When orography is not significant, or when the effect can be neglected, the term 'non-orographic' is used in this Guide. Traditionally these effects have been described as 'topographic'.

In orographic situations, the mean wind velocity is magnified but the turbulent component is not.

HOW WIND ACTS ON BUILDINGS

3.1 Flow around an obstruction

Wind actions on a building result from the way the air is deflected around and above it. How much passes around the sides and how much flows overhead will depend on the proportions of the building, mainly its height and breadth as viewed in the wind direction. Although a simpler two-dimensional view can be taken of the flow around a linear element, or the lower part of a tall building, it is generally necessary to visualize the flow in three dimensions.

Momentum is lost at the windward face, resulting in positive pressure. Continuity of flow demands that the wind accelerates around the obstruction, resulting in negative (sub-atmospheric) pressure, or suction, on the sides and roof. At the rear, there is a relatively stagnant wake, also of negative pressure, before the flow recombines some distance downstream.

3.2 Detachment

There is no such thing as a streamlined building. Most building shapes are bluff bodies from which the flow will become detached, usually, but not always, at corners. Rotation (eddying) is induced in the body of air between the detached flow and the building, generating high local suctions in this zone. If the detachment is at a windward corner of the building, reattachment further along is possible. Lines of reattachment are not anchored in position, so local pressures can fluctuate wildly. There is potential for various types of instability, in which the building's own flexibility is liable to play a part (see Section 4.2). Such dynamic interaction, in which action and effect reinforce one another, would be described as 'aerolastic' behaviour. Most low to medium rise buildings will be stiff enough not to exhibit this, but all buildings are subject to the pressure fluctuations.

3.3 Surface pressures

At any point on the surface, pressure fluctuates in magnitude (and even between positive and negative), due to gustiness of the oncoming wind and the consequences of its interruption by the building.

Peak pressures on the various surfaces are represented by non-dimensional pressure coefficients, c_p, which are multiplied by the peak velocity pressure q_p to obtain the pressure w acting on the surface/zone in question. From the Bernoulli expression (or Newton's second law) velocity pressure $q = 0.5\rho v^2$. In a one-dimensional view, q would represent the pressure generated by bringing the flow to a standstill. It is also known as stagnation pressure or dynamic pressure.

Coefficients are mainly derived from extreme value analysis of integrated multiple instantaneous pressure measurements in a wind tunnel. The model is rotated at various angles to cover the quadrant of wind directions (45° either side of face-on) for which the coefficients are relied upon to be valid.

3.4 Size effect

The gusty nature of wind means that the design pressure on a 1 m^2 area is greater than that for a 10 m^2 area, as gusts are limited in extent and the most intense gusts are the smallest ones. In the UK, Table NA.3 (or Table 5.1 of this Design Guide) prescribes size factors to allow for this. EN 1991-1-4 provides for different pressure coefficients for different loaded areas, to do so in another way, but these are not adopted in the UK.

3.5 High local suctions

High local suctions occur downstream of corners, in the zones of detachment. They govern the cladding design and can generate severe uplift conditions for individual roof beams and purlins. Where faces are inclined to the wind (as in a sloping roof) these zones can also influence the overall lateral force on the structure.

The most severe local roof suctions typically result from the formation of a vortex from the leading corner, with wind at an angle around 45°, inducing lateral flow and in turn a rotational (helical) flow pattern. In a vortex, kinetic energy from the flow is concentrated into accelerating a small mass of air, with intense but localized damaging power. Pressure coefficients in the areas at risk can locally attain the value of −2.6.

3.6 Overall forces

For structural engineering, the primary objective is normally to establish overall lateral forces on the structure in each of two directions at right angles. These forces result from a combination of positive pressure on one windward face and negative pressure on one leeward face. It is statistically unlikely that both the front and back of a building will experience their peak wind actions simultaneously. A reduction factor to account for this lack of correlation may be applicable when calculating the combined effect on the structure as a whole. Moreover, the peak values of pressure on the two faces may not coincide in wind direction either, bearing in mind that each has been separately assessed for a full quadrant of incident wind. Force coefficients, based on wind tunnel testing designed to capture the overall action (either directly by high frequency force measurement or by integration from simultaneous surface pressure readings), are inherently superior because no undue conservatism arises.

Friction on the side and roof faces of the building adds to the wind forces which result from pressures acting normal to the other surfaces. This ‘skin’ friction, quite distinct from mechanical friction, is actually the drag on small scale surface protuberances. The greater the area exposed to the flow, the greater the frictional force. In principle friction should be added when not allowed for in the force coefficient, or if overall force is calculated by vectorial summation of surface pressures. Fortunately it is often small enough to neglect.

The conventional view of wind as acting in two principal directions at right angles to the faces of a rectangular building is convenient because the lateral resistance of the building will usually be organized in the same two directions. Tabulated coefficients implicitly allow for non-perpendicular wind. What they cannot be expected to allow for is non-rectangular buildings (some regular shapes excepted). A common engineering expedient is to calculate for an imaginary building whose plan shape is the enclosing rectangle. This is hardly likely to underestimate overall forces but may not be realistic for local pressures.

HOW BUILDINGS REACT TO WIND

4.1 Dynamic amplification

Buildings do not simply lean backwards when wind force acts. They also sway to and fro in line with the wind, at their natural frequency. There is some degree of dynamic magnification of the displacements and other effects (internal member forces) that would result from application of the wind force in static fashion. This magnification is accounted for by a dynamic factor in the Standard.

Because turbulent wind provides a continuing supply of energy to sustain oscillation, damping is all-important in limiting its magnitude. Damping is impossible to predict with certainty, as non-structural components and furnishings of the building can often absorb more energy than the frame, but an estimate must be made for design purposes and EN 1991-1-4 Table F.2 suggests that a value of $\delta = 0.05$ is appropriate for typical steel buildings. Note that δ is the logarithmic decrement. The critical damping ratio is given by:

$$\xi = \frac{1}{\sqrt{1 + (2\pi/\delta)^2}}$$

$$\approx \text{(for low damping) } \delta/(2\pi)$$

A logarithmic decrement of 0.05 corresponds to just under 0.8% of critical damping. For composite construction, or with a reinforced concrete core, δ may be taken as 0.08 (1.27% of critical).

These damping values are ‘informative’, so designers are, in principle at least, free to choose different values. Measurements on actual buildings display a huge scatter and do not support the customary distinction between material types, except for tall buildings. There is a trend for damping to decrease as height increases, presumably because proportionately less energy is dissipated into the ground. Very tall buildings (outside the scope of this Design Guide) are acutely sensitive to damping assumptions, and their design wind effects can be more than doubled by dynamic amplification.

4.2 Cross-wind oscillation

Buildings can also be induced to sway in the y-direction. For a tower block, cross-wind oscillation due to von Karman vortex shedding (rhythmic detachment and reattachment alternating between opposite sides) may be troublesome when the vortex shedding coincides with a natural frequency of the structure. Since this can occur at a wind velocity which is relatively low, and frequently experienced, it raises issues of serviceability (occupant comfort) and fatigue. It is one of the reasons for recommending specialist wind engineering advice for higher and more slender buildings (see Section 8).

Vortex-induced vibration is only one of a number of aerodynamic and aerolastic instabilities which receive attention in EN 1991-1-4, the NA and the PD. The subject area is rarely of concern for conventional buildings within the scope of this Design Guide. However designers should be aware that external elements of low-rise buildings, notably cable, bar or CHS stays, can be vulnerable to the same phenomena (see BS EN 1993-1-11[7], Section 8).

There is a lack of international consensus on the treatment of aerolastic instabilities. Consequently, NA.3.5 states that Annex E of the Standard 'should not be used' in the UK. Annex A of the PD is provided as its replacement.

4.3 Interference between buildings

Mention should also be made of aerodynamic interference between neighbouring buildings. A tall building can scoop down high velocity upper air to the detriment of a low building in its immediate vicinity. EN 1991-1-4 A.4 offers design rules which may be of service (if the higher building is already present or planned).

It is also possible for surface suctions to be increased, with implications for cladding design, if two buildings are separated by a small gap. This type of 'funnelling' is dealt with in notes d and e under Table NA.4 and also in PD 6688-1-4, 3.9.3.1.

THE CALCULATION PROCEDURE

5.1 General

The procedure described here is for the calculation of characteristic values of overall wind actions on a building up to 100 m (or, in an orographic situation, 50 m) in height above ground.

The procedure is presented in 25 stages so as to allow for every possible influence embraced by BS EN 1991-1-4. In practice it would be rare for all of these to apply in any one case. Several stages will not apply if the site is out of town, and even in town the consideration of displacement is optional. Other stages will apply only if orography, or friction, proves to be 'significant'.

- Stages 1 to 11 evaluate peak velocity pressure q_p, the key intermediate result, without regard for orography
- Stages 12 to 17 cater for orographic situations, which will usually increase the peak velocity pressure
- Stages 18 to 25 determine overall force on a building (or component) by means of a force coefficient

Forces on buildings can alternatively be derived from surface pressures as described in Section 6. For a calculation of overall lateral force by vectorial summation of surface pressures, the procedure is taken as far as Stage 20 (at which the highest value of $q_p c_s c_d$ is identified). Stages 22/23 are also relevant, as friction, if significant, must be added to the summation.

For an overall force calculation, z (the height for which the wind is calculated) is generally taken as equal to the height of the building, measured to the top, which may be a ridge or a parapet. For all normal buildings, this is what BS EN 1991-1-4 requires. Exceptions to this rule are off-ground spheres, signboards, bridges and some types of canopy – all outside the scope of this Design Guide. Users will encounter the term 'reference height' and symbol z_e for the height for which the wind is calculated, but 'reference height' has more than one meaning. Confusion between z, z_e and z_s (used to calculate the altitude factor) can be minimized by avoiding the z_e term.

For some purposes, the height z for which q_p is determined may vary. For example, it would be appropriate to calculate for a lower level ($z < h$) in a separate calculation for an individual element that is not as high as the building (see Section 9.3 for an example), or to calculate a local pressure part way up a windward face. So-called 'division by parts' is only appropriate for the windward face, and then only if the building is taller than its cross-wind breadth. More advice on division by parts is given in Section 6.4.

5.2 The influence of orography

Initially, the procedure calls for a calculation without regard for orography, even for a situation which is clearly 'orographic'. This is because the 'non-orographic' calculation might produce a more onerous result.

The reason for the 50 m height limit in an orographic situation is that the simpler of the two treatments in the NA (using exposure factors) becomes invalid above this height. The NA requires a more elaborate treatment (using roughness factors) for a building over 50 m high in an orographic situation. The descriptions 'simpler' and 'more elaborate' are not used in the NA itself, but the latter corresponds to Expression (NA.4b) and the bottom two boxes in each of its flow charts (Figures A.NA.1 and A.NA.2).

For a building over 50 m in height, the simpler procedure presented in this Section can confidently be followed where it is obvious that the situation is **not** an orographic one.

Where the situation of a building over 50 m **is** orographic, the more elaborate treatment (outlined in Appendix A of this Design Guide) must be pursued. This course of action can also be embarked upon if it is not immediately obvious whether the orography is 'significant'. There will be no need to change course if, in some or all sectors, orography proves insignificant, because the more elaborate treatment is of general application. Without orography, both treatments should give the same result.

5.3 Calculation of peak velocity pressure

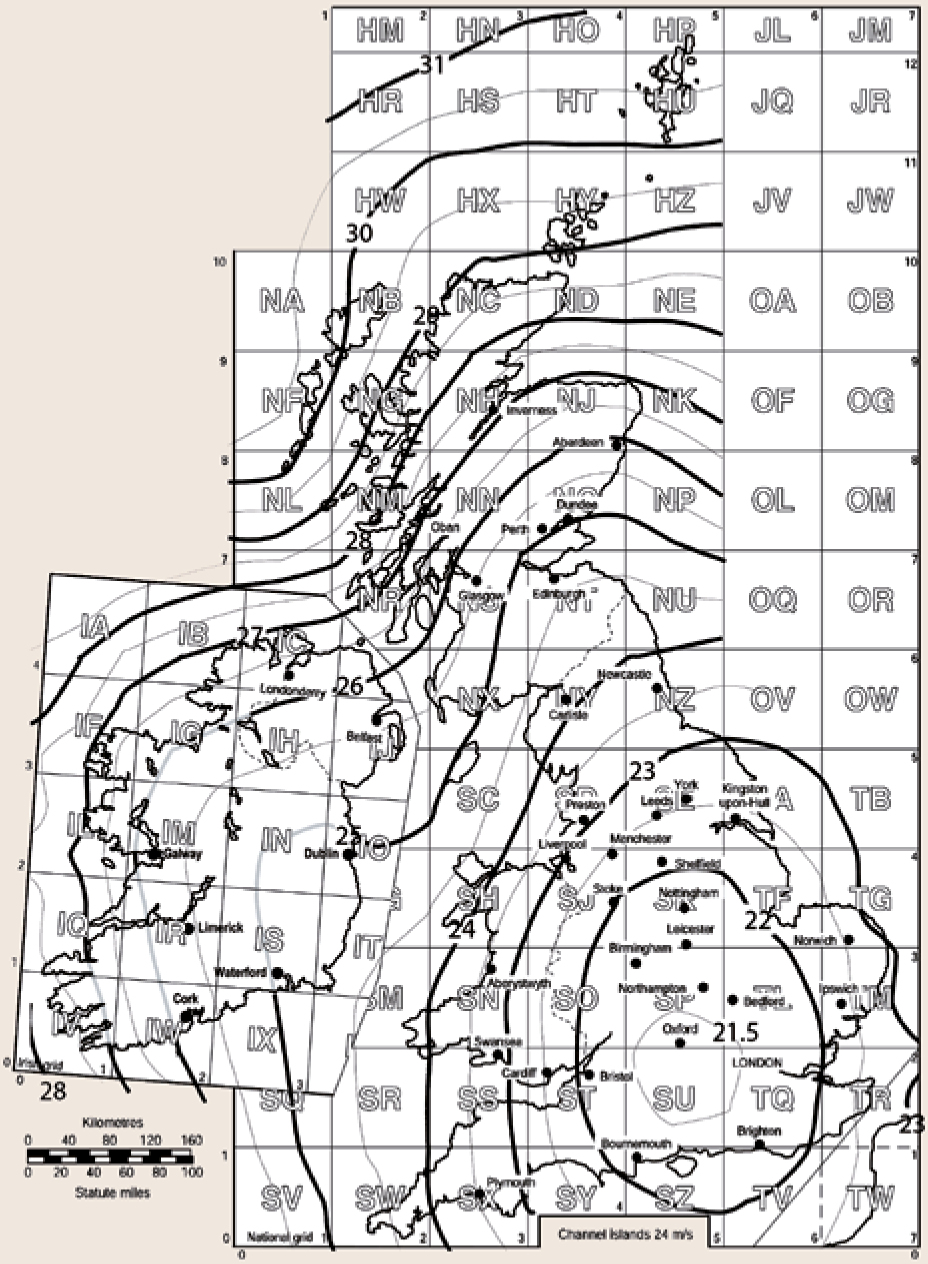
Stage 1 Obtain v_{map} from the UK wind map

The 2010 UK wind map is reproduced as Figure 5.1.

The map wind speed, symbolized here as v_{map} (short for $v_{b,map}$), is the 10 minute mean wind velocity with a 0.02 annual probability of exceedance, equivalent to a 50 year mean recurrence interval ('return period'). Note that in order to minimize confusion the terms 'fundamental', 'basic' and 'fundamental basic' are avoided in this Design Guide.

The 10 minute averaging time for the map wind speed is a departure from the hourly mean on which the 1995 wind map in BS 6399-2 was based. Over a shorter period, mean velocities are higher, simply because there is less opportunity for a lull to cancel out a peak in the record. 10 minute mean velocities are (empirically) 6% higher than hourly mean velocities.

Other changes from the 1995 map reflect the availability of improved records. With 30 years of record, as opposed to 11 years in BS 6399-2, extreme value statistical analysis can safely predict a characteristic velocity slightly lower than before.



Contours of v_{map} are in m/s and the grid squares are 100 × 100 km

Figure 5.1
2010 wind map from NA to BS EN 1991-1-4: 2005+A1:2010

More obvious are the regional variations which result from some substitutions and reappraisals of anemometer stations. These have most effect in central highland Scotland (where map winds have become stronger) and part of eastern coastal England (where the change is favourable). A calibration study[8] details these differences.

The public domain data used to plot the wind map, together with other graphically presented information in the NA, can be freely downloaded in csv format[9].

Stage 2 *Calculate the altitude factor* c_{alt}

High ground presents an obstacle to the airstream in the atmospheric boundary layer and the air must accelerate to maintain continuity of flow. Anemometer stations vary in altitude, but this variation has been allowed for in the preparation of the wind map. Hence v_{map} is the wind speed to be expected if the anemometer were 10 m above sea level, rather than its actual altitude. The reverse adjustment must now be made to correct for the altitude and height of the building under design. For a building at least 16.7 m high, the value of the altitude factor is given by:

$$c_{\mathrm{alt}} = 1 + 0.001A(10/z_{\mathrm{s}})^{0.2}$$

in which:

A is the site altitude (ground level in front of the building in metres above sea level)

z_{s} is $0.6h$ where h is the height of the building (in metres above ground level). If the wind calculation is for an individual element, rather than the building as a whole, z_{s} is obtained from EN 1991-1-4 Figure 6.1.

If $z_{\mathrm{s}} < 10$ m (buildings less than 16.7 m high) the expression reverts to:

$$c_{\mathrm{alt}} = 1 + 0.001A \qquad \text{(as in BS 6399-2)}$$

As noted in NA.2.5, this shorter expression is conservative and may be used for buildings of **any** height, at the designer's option. The full expression will be most beneficial where both the building and its site are relatively high. Elsewhere, for the majority of buildings perhaps, the simplicity of the shorter version may retain its appeal.

If advantage is taken of the full expression, the altitude factor depends on the building as well as its site. Moreover, different altitude factors could be calculated for different purposes. For example cladding design for a tower block might legitimately be based on z_{s} to mid-height of the topmost panel, yielding an appreciably lower c_{alt} than that used for the structural design of the building (based on $z_{\mathrm{s}} = 0.6h$).

It should be pointed out that the symbol z_{s} is used here, in place of plain z given in NA.2.5, to avoid confusion between this 'reference height' z_{s} and height z $(= h)$ for which the peak velocity pressure is calculated. EN 1991-1-4 Figure 6.1, in which 'reference height' z_{s} is defined, appears in its Section 6 headed 'Structural factor $c_{\mathrm{s}}c_{\mathrm{d}}$'. In UK practice the recommended approach is to use separate size and dynamic factors in preference to a 'structural factor', largely ignoring Section 6 of the Standard. In this Design Guide, z_{s} is only encountered in the altitude factor formula.

Stage 3 Choose a sector size and orientation for consideration of directional effects

Most of the parameters which enter into a wind calculation are directional, or potentially so. Influences of note are:

- Regional climatic bias. Throughout the UK south-westerly to westerly winds dominate, in both frequency and severity. Figure 5.3 presents this variation graphically
- Distance from the shoreline, up to an arbitrary 100 km
- Orography (hills and cliffs accelerating the oncoming wind), which will almost always vary with direction
- For an urban site, distance from the edge of town
- Displacement height (see Stage 5) may not be the same in all directions
- Size and dynamic factors both depend on breadth, which commonly varies between the principal directions. Moreover, size factor is influenced by zoning and displacement, so may vary from one sector to another

Designers have the option of adopting a 'non-directional' approach, combining the most onerous of every influence from any direction. This is simple and safe, but often excessively conservative because the most onerous directional influences do not align.

There is almost always advantage to be gained by subdividing the compass into a number of sectors and calculating the directional parameters separately. If twelve sectors of 30° are chosen, all twelve of the resulting wind actions will probably be lower than that for the non-directional approach, and it will also be possible to extract separate results for a building whose resistance is not the same in all directions. In principle, any number of sectors could be chosen, but in practice there is unlikely to be much to gain from more than twelve. Indeed, there may not be much to lose by choosing four sectors of 90°, i.e. quadrants. The calculation process presented in this Design Guide is based on twelve sectors, but may readily be adapted to quadrants.

The advantage to be gained from a directional approach varies from one location to another and could only be quantified by doing the calculation both ways. However, it will sometimes be obvious. For example, a site in Sunderland, a city on the coast but over 100 km from the shoreline in all the directions for which c_{dir} (see Figure 5.3 of this Design Guide) exceeds 0.82, can benefit substantially.

The orientation of the sectors, as well as their number, is a matter of choice. There is no obligation to adopt that presented in the NA, whose Table NA.1 lists directional factors for twelve 30° sectors, starting with one centred on North. Ideally, the sector orientation should be chosen to suit the building. In most buildings, lateral resistance is organized in two orthogonal directions. It is for these principal directions that overall wind actions are required, so the sectors (or quadrants) should be centred on the building's own axes. Any sector wholly or partially encompassed by a quadrant extending 45° either side of the axis can (at Stage 20) govern the design wind force in that direction, so if the (30°) sectors do not 'suit the building' it is the highest of four results that must be taken, rather than the highest of three. The diseconomy could be compounded if the sector with the highest result happens to straddle the 45° line, and thus govern both principal directions. This is bound to happen with a calculation initially based on four quadrants of 90°, unless they are centred on the building axes.

It is therefore advisable to avoid potential diseconomy, and complication at later stages, by orienting the sectors or quadrants to 'suit the building'. Of course this is only possible if the building is a regular one, whose own orientation is settled at the time of the wind calculation. It is worth mentioning that most of the benefits of a directional calculation remain available with arbitrarily chosen sectors (such as 345° to 15°, 15° to 45°, 45° to 75° etc.). Even the most onerous result from arbitrary quadrants, applied in every direction, can deliver advantage over a non-directional calculation.

Local geography might also motivate choice of sector orientation. One example is an escarpment, whose orographic influence could, by judicious orientation, be contained within just six (30°) sectors, or two quadrants. Another is a sheet of water whose shoreline influence could be contained within a carefully oriented sector. However there is a risk that the advantage gained could be diminished or negated if that sector were to straddle the 45° line at Stage 20. Trial and error may be called for.

To summarize, options for sector size and orientation are:

- Twelve 30° sectors, chosen to suit the building or the geography
- Four quadrants (90° sectors), chosen to suit the building or the geography

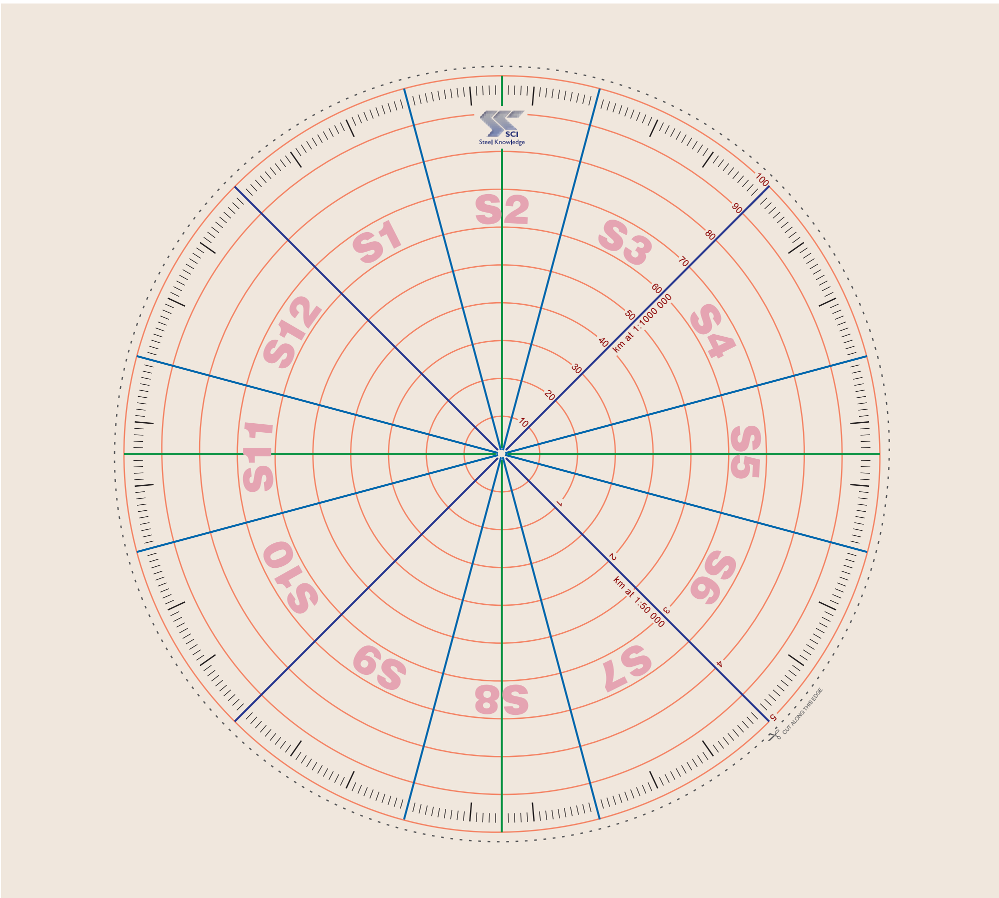


Figure 5.2
SCI wind protractor (half-scale)

- Any other consistently applied directional subdivision of the full 360° around the site
- A non-directional approach (single '360° sector') taking $c_{\text{dir}} = 1$

Although 30° sectors may be regarded as the default option, the second (quadrants) option is also recommendable, especially for a preliminary calculation. In comparison with twelve sectors, all that can be predicted with certainty is that the wind actions will turn out no smaller, but the saving in manual effort is readily appreciable.

The SCI Wind Protractor (shown at half scale in Figure 5.2 and at full scale in Appendix C) is designed to facilitate the process at this and later stages. It may be photocopied onto transparent film and used as an overlay on maps and air views.

If the green lines of the protractor are aligned with the axes of the building, each group of three 30° sectors will consolidate straightforwardly into a quadrant at Stage 20. This is what is meant by 'sectors to suit the building'. If the second option (quadrants from the start) is chosen, Q1 = [S1 + S2 + S3], Q2 = [S4 + S5 + S6] etc.

Once the sector orientation has been decided, mark North on the protractor for use at later stages.

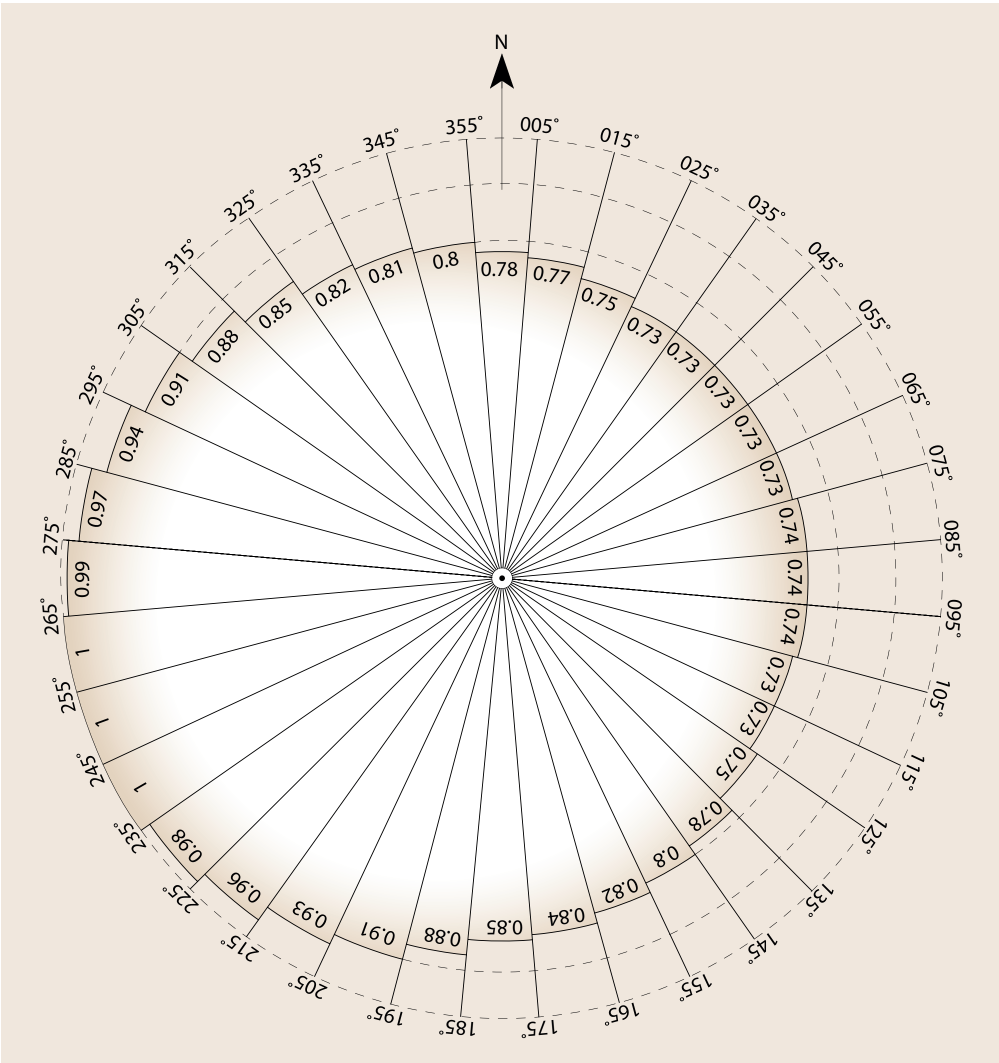


Figure 5.3 Directional factor c_{dir} for the UK at 10° intervals

Stage 4 For each sector, determine the directional factor c_{dir}

The directional factor can be found from Figure 5.3.

Figure 5.3 is based on Table NA.1, with values at 10° intervals. To obtain directional factors for the chosen sector size and orientation, the SCI Wind Protractor can be placed over Figure 5.3 with North at the top. For 30° sectors, the directional factor may be read at the centreline of each sector. For larger sectors, the largest c_{dir} encompassed by the sector should be taken.

There will always be at least one sector for which c_{dir} is 1.0.

Directional factors are a statistical measure of design wind velocity for a given direction, relative to the worst from any direction. There is no regional variation within the UK; the same factors apply in Shetland, Scilly and points between.

Stage 5 For each sector, determine the displacement height h_{dis} (for buildings in town)

If the site is not in town, or conservatively, take $h_{\mathrm{dis}} = 0$ and proceed to Stage 6.

'Displacement' allows for the sheltering effect of dense upstream urbanization. The base of the atmospheric boundary layer is considered to be at displacement height h_{dis}, which is taken as 80% of the average height h_{ave} of the upstream buildings, but not to exceed 60% of h, the height of the building under design. Displacement subtracts from the height (z) for which the wind is calculated, reducing wind action on the building as a whole; it does **not** imply a wind-free zone below h_{dis}.

It is always safe to underestimate displacement. Safer still, it may be ignored, taking $h_{\mathrm{dis}} = 0$ so that $(z - h_{\mathrm{dis}})$ becomes equal to z.

For displacement to take effect, the buildings generating it need to extend at least 100 m upstream, and a reasonable density of urbanization is required. Building height can be far from uniform in British cities and towns, so assessment of displacement may require judgement. It is quite likely that h_{dis} will vary sector by sector. Air photographs or satellite imagery can be a useful supplement to inspection on the ground.

The effect reduces if there is open space immediately in front of the building (such as a square, or even a relatively wide road). EN 1991-1-4 Expression (A.15) gives a formula which is presented graphically in Figure 5.4.

Not all suburbs are dense enough to provide reliable displacement. BRE Digest 436[10] suggests that a minimum 8% coverage on plan, or 12 houses per hectare, is called for. Modest displacement is proportionately fragile; a suburban level of displacement might not survive the crossing of a wide road.

Although trees can be effective in the same way, a designer relying on a forest for displacement would have to be very confident of its permanence. A NOTE to NA.2.11 advises that h_{dis} should be taken as zero for sites in country terrain. In contrast, urbanization is generally considered irreversible, though buildings are not permanent

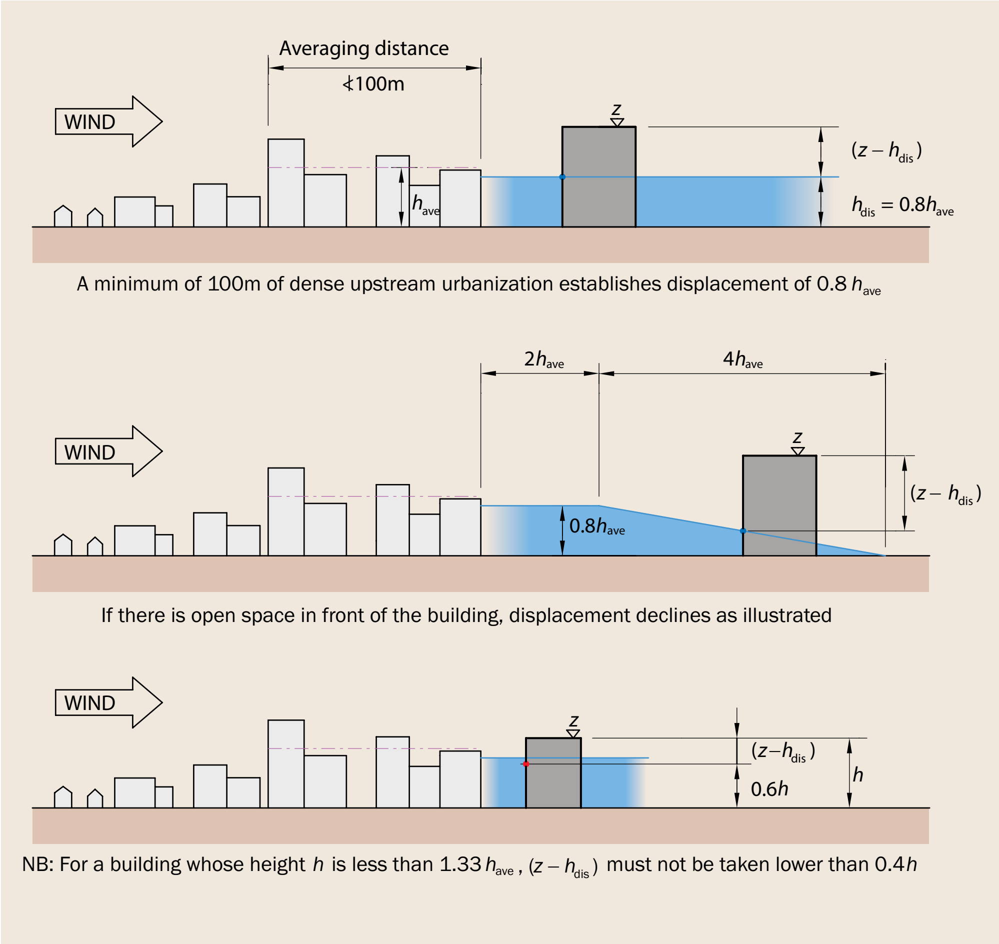


Figure 5.4
Displacement height
(from EN 1991-1-4, A.5)

and regeneration can create open space. Figure 5.5 provides two cautionary examples from Bradford, Yorkshire. At bottom left, outlined in green, a planned public open space (City Park); at top right, outlined in pink, a stalled retail development site cleared in 2006, now partially landscaped (Bradford Urban Garden). Both were once densely built up.

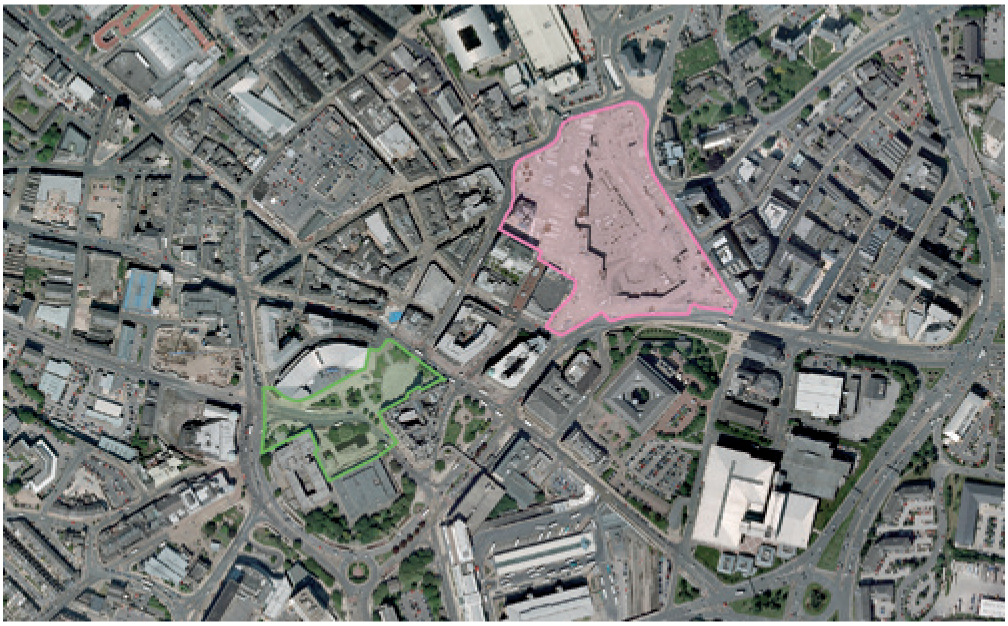


Figure 5.5
Air view of
central Bradford

RGB Aerial Photography
© GeoPerspectives

To summarize: displacement height h_{dis} should be taken as the lowest $0.8h_{\mathrm{ave}}$ in any direction encompassed by the sector, subject to any reduction due to foreground open space (see Figure 5.4). The value of h_{dis} must not exceed $0.6h$. If upstream building height is uncertain, it should be cautiously underestimated. If upstream building density is in doubt, h_{dis} should be taken as zero.

Stage 6 For each sector, determine the distance from the closest shoreline to the site

Ground, even open ground, is rougher than water so the primary influence on the atmospheric boundary layer is the distance the wind has travelled since landfall. A map covering the land area within 100 km of the site can be used to determine the distance from the closest shoreline to the site, in each sector.

Distances in excess of 100 km need not be evaluated. Shoreline usually means the sea, but inland water will count if it is closer than 1 km **and** more than 1 km in radial extent.

Figure 5.6
SCI wind protractor centred at Sheffield on 1:1000 000 map
The Times Atlas of the World (www.timesatlas.com)

Figure 5.7
The Severn estuary
CHELYS (www.eosnap.com)

For many locations in the UK the nearest shoreline is an estuary, and it will not always be easy to judge its inland extent. A case in point is the Severn estuary, fairly straight, deeply penetrating and aligned at 220° to 235°, which is practically coincident with maximum directional factor (Figure 5.3). A reasonable assumption is that the shoreline extends to Frampton on Severn, the point above which the river becomes tortuous and less than 1 km in width. Measuring to Frampton would be appropriate for a location such as Evesham, 45 km inland in line with the estuary. However, for a location such as Hereford, 40 km distant but well off line, the Severn at Frampton has negligible influence and the shoreline in this direction is effectively the Solent. Even in a more south-westerly direction, for which Hereford's closest shoreline might be taken around Newport (60 km), it may be argued that 40 km of Severn estuary, preceded by over 70 km of Devon and Somerset, and followed by another 60 km over land, can hardly be equivalent to open sea. On the other hand, the estuary would undoubtedly represent sea for a site in Newport itself. BRE Digest 436[10] offers the rule of thumb that estuary can be ignored if its radial extent is exceeded by that of land upwind of the water **and** by that of land between water and site. By this authority Hereford's nearest shoreline is at Port Talbot (90 km). These and other interpretations of the rule are arrowed on the map in Figure 5.8.

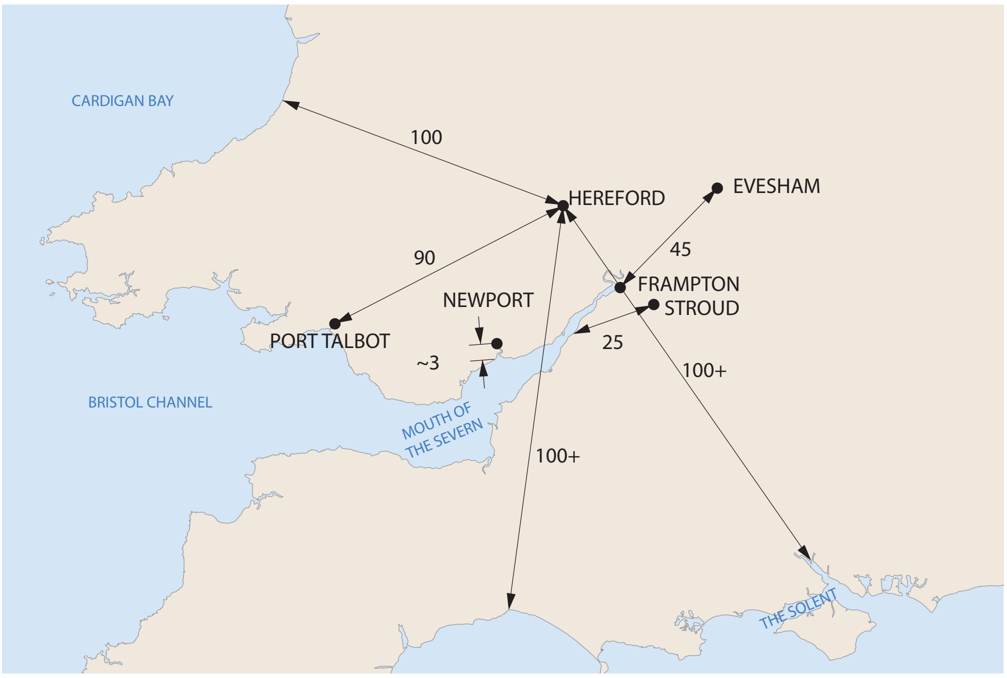


Figure 5.8 Map of the Severn to illustrate the BRE Digest 436 estuary rule (distances in km)

The same rule can be applied to areas of inland water which are more than 1 km in upwind extent. Thus the influence of Lough Neagh, for example, would extend almost to Belfast.

Clearly the presumption of a stepwise one-way progression from sea to country to town represents a crude simplification. Methods are available[11] for a less restrictive and more nuanced assessment of the cumulative effect of upwind terrain variation, but the approach in the NA is simple for non-specialists to apply and, in most situations, not unduly conservative.

Stage 7 For each sector, determine the exposure factor c_e

The exposure factor can be obtained from the graph of Figure NA.7, reproduced here as Figure 5.9.

Ordinate $(z - h_{dis})$ is normally the height of the top of the building above the displacement level, as illustrated in Figure 5.4. If the site is out of town, or if displacement is unavailable or ignored, $(z - h_{dis})$ becomes z (height above ground). The left hand edge of the graph applies at the shoreline and up to 100 m inland. The right hand edge of the graph applies upwards of 100 km inland. The bottom edge of the graph applies between ground level and 2 m above h_{dis}.

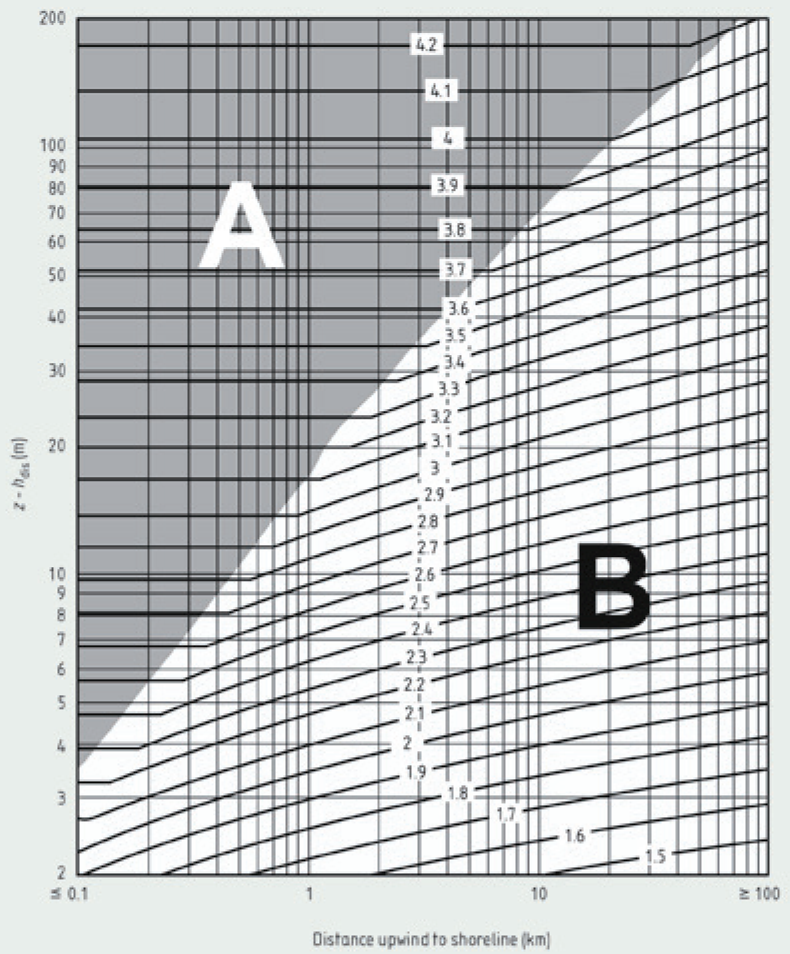


Figure 5.9
Exposure factor c_e
(Figure NA.7)

Exposure factor c_e accounts for the variation of wind pressure with height, together with the upwardly propagating frictional and turbulence-inducing effect of the ground. Even near ground level, c_e is greater than 1 because gustiness is superimposed on the mean wind.

Note also, in the same figure, whether zone A or B applies. This will be used later in the determination of size factor. If the site is in town, this zone assignment is a provisional one which may be overridden at Stage 10.

The graphs used at Stages 7 and 9 are logarithmically presented, so interpolation is not straightforward. This can be circumvented by using freely downloadable software from RWDI[12], which delivers a combined factor $c_e\, c_{e,T}$ (see Figure 9.4 of this Design Guide).

Stage 8 For each sector, determine the distance to the edge of town (if the building is in town)

Ignore this stage and proceed to Stage 10 if the site is not in town.

For an urban site, the additional ruggedness of the upstream buildings exerts a secondary influence on the atmospheric boundary layer, represented by the town terrain correction factor $c_{e,T}$. This always has an ameliorating effect, if any. It takes time and distance to propagate upwards, so a tall building not far into town might gain no benefit.

The distance to the nearest edge of town can be determined from a 1:50 000 map, air photography or otherwise. The shading used for built up areas on Ordnance Survey maps gives a reasonable indication of the edge of town.

As with displacement, a minimum of 100 m of upwind urbanization is needed to establish the beneficial effect of town terrain. Unlike displacement, however, it does not rapidly decay where the urban grain is interrupted by a wide road or a square.

Parks and other extensive open spaces within town may call for judgement to be exercised. It is always safe to treat them as country, but probably reasonable to ignore open space whose radial extent is small relative to that of the built up areas preceding and following it, especially if it is more than 1 km away from the site. A Park Lane address (point A) should be treated as country (for sectors exposed to Hyde Park) whereas a North Audley Street site (point B) would be in town (but only by 250 m). 1 km further downwind (by Regent Street, point C) it might be judged reasonable to discount the 'countrifying' influence of Hyde Park. These locations can be identified on Figure 5.10.

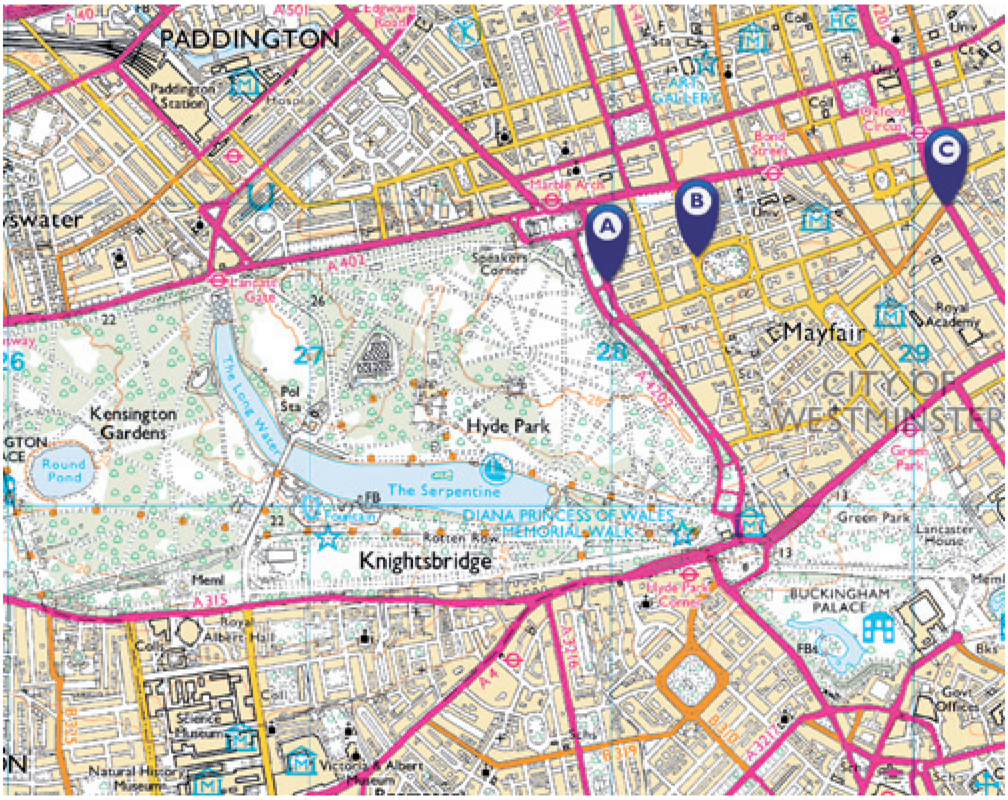


Figure 5.10
Hyde Park and Mayfair, London

Stage 9 For each sector, determine a reduction factor $c_{e,T}$, to account for town terrain

The reduction factor can be obtained from the graph of Figure NA.8, reproduced here as Figure 5.11.

Note that symbol ≤ before the 0.1 km at bottom left of this graph is incorrect as a site this close to the edge of town is to be treated as being in country terrain and $c_{e,T} = 1$ for the sector(s) in question.

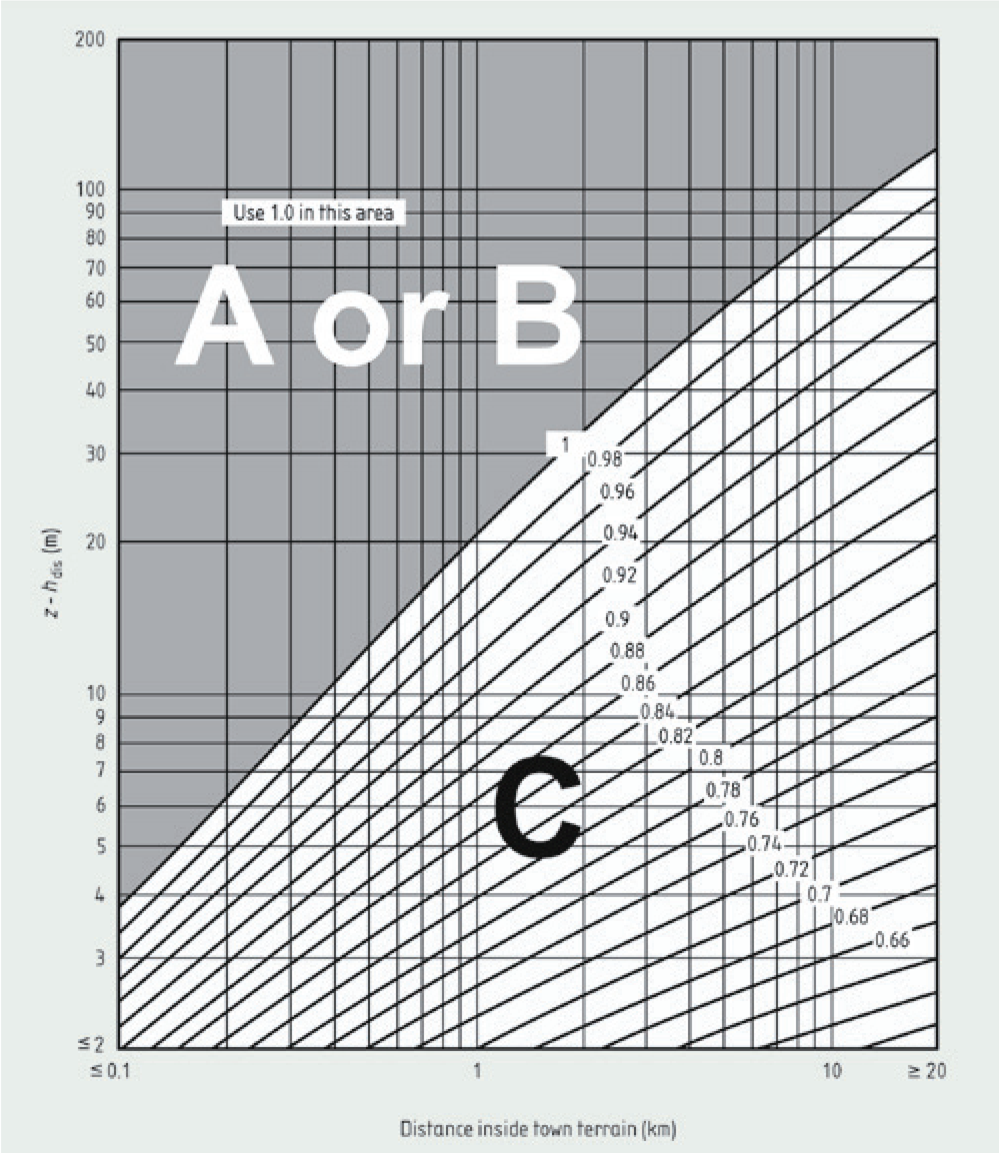


Figure 5.11 Exposure correction factor $c_{e,T}$ for sites in Town terrain (Figure NA.8)

Stage 10 For each sector, determine a size factor zone (A, B or C)

The unshaded part of the graph, where $c_{e,T}$ applies, is Zone C, overriding the original zone assignment from Figure NA.7. In the shaded part, where $c_{e,T} = 1$, high buildings near the edge of town retain their original (Stage 7) assignment to Zone A or B.

The freely downloadable software referred to at Stage 7 also gives the size factor zone (in brackets); see Figure 9.4 of this Design Guide.

Stage 11 For each sector, calculate peak velocity pressure ('non-orographic')

The peak velocity pressure is given by:

$$q_p = 0.613(v_{map} \times c_{alt} \times c_{dir})^2 \times c_e c_{e,T}$$

In this expression $c_{e,T}$ is 1 if the site is out of town (or not far enough into town for Figure 5.11 to give $c_{e,T}$ less than 1).

The variables in the expression have been evaluated in the preceding Stages 1, 2, 4, 7 and 9 respectively. Air density, although not a constant, is treated as such in wind calculations. The UK retains the familiar 1.226 kg/m^3, differing from the value recommended in EN 1991-1-4 (which is 1.25 kg/m^3). 0.613 represents half the density of air.

With v_{map} entered in m/s, q_{p} is output in Pa (N/m^2).

Thus far, the peak velocity pressure has been calculated on the assumption of no orographic influence.

Stage 12   Determine whether orography is potentially 'significant'

A contour map covering the ground within a 5 km radius of the site may be consulted for this purpose. If contours are difficult to discern in urban areas, Ordnance Survey Open Data[13] may be helpful (see Figure 5.12).

Figure 5.12
Open source contours

At this stage it is necessary to investigate whether orography is, or may be, 'significant'. The air flow is accelerated by rising ground on its approach to the building. With gentle slopes over long distances the effect is small (and is accounted for by the altitude factor); it becomes significant where there is local and relatively abrupt level change.

In an 'orographic' situation, the directional approach can be used to advantage. Unless the building is set atop a conical hill, there will be sectors in which orography is not significant. It will often be possible to declare a sector 'non-orographic' by inspection and rules of thumb.

There is no need to investigate any sector within which the immediately surrounding ground is flat, or higher than the site, over a radius of 1 km.

Even if the ground rises towards the site, an upwind slope less than 3° (0.052 radians, 1 in 20) is considered insignificant.

Since large scale orography is accounted for by the altitude factor, it may also be judged reasonable to take $c_{\mathrm{o}} = 1$ if there is equally high or higher ground on the near horizon, continuously within the sector and close enough to shelter the site, even with a valley intervening. ‘Close enough’ is a matter of judgement. The 8 km radius embraced by PD 6688-1-4 Figure 2 gives some indication, but SCI recommends a more cautious approach, looking for shelter within a 5 km radius (that of the SCI Wind Protractor on a 1:50 000 map).

Even where a hill or ridge is relatively steep, the building will only experience the full effect if it is sited near the crest. At a site less than half way up the slope, or some distance beyond the crest, the effect of orography may be ignored (see Figure 5.13).

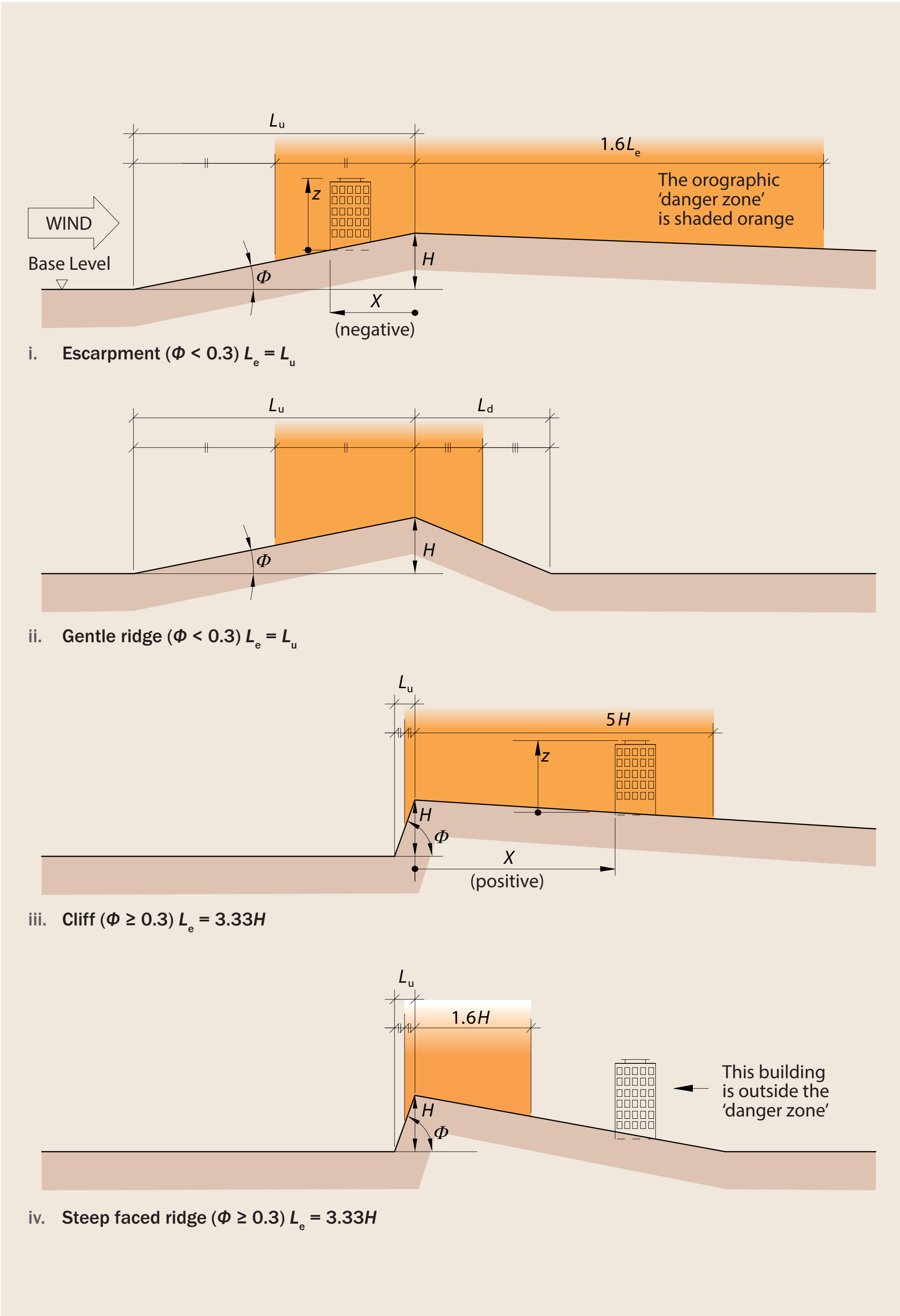


Figure 5.13 Orographic zone of influence (a re-presentation of Figure NA.2)

The difference between an escarpment and a ridge (or a hill treated as a ridge) is that the latter has a downslope ϕ_d of at least 0.05 (≈ 3°). A cliff (or a steep-faced ridge) has an upslope ϕ of at least 0.3 (≈ 17°).

Although the 'half way up' rule applies in all cases, the 'half way down' rule only applies in the case of a gentle ridge. If the ground is lower on the downwind side, the 'half way down' rule can be interpreted as 'half way down to base level'.

EN 1991-1-4, 4.3.3(1) allows an orography factor less than 1.05 to be treated as insignificant (i.e. taken as 1.0). Until an orographic calculation has been carried out, the orography factor is unknown. So a sector identified as potentially 'orographic' at this stage may, after calculation (Stage 15), be reclassified as 'non-orographic'.

An automated calculation of orography is embodied in commercially available software BREVe[14], which uses a geographic data base of Great Britain to take its users as far as Stage 17 of the procedure in this Design Guide. Unfortunately, this cannot replace judgement, as the kilometre squares of its data base are too coarse to reliably capture and quantify orographic effect.

To summarize: orography may be judged insignificant (c_o taken as 1) if, throughout the sector in question, any one of the following applies:

- The upstream slope is less than 3° (0.052 radians, 1 in 20). On a map with a vertical interval of 10 m, this corresponds to 5 contours per kilometre grid square
- The site is less than half way up the upstream slope
- The site is sufficiently far downwind of the crest to escape the 'danger zone' shaded in Figure 5.13
- Uninterrupted shelter is available from surrounding ground at least as high as the site over the entire angle subtended by the sector

For any sector(s) in which orography is potentially significant, continue from Stage 13. Otherwise go to Stage 18.

Stage 13 For each sector, determine the geometry of the orographic feature

Idealize the landform as either a ridge or an escarpment. Both forms are idealized with a constant upslope with a distinct starting line from level ground (base level), followed either by a pronounced and constant downslope (a ridge) or continuing high ground (an escarpment).

These are the only profiles recognized by the Standard. The designer must judge where the slope begins and ends, not just its average gradient. This is simple for a cliff, but inland slopes are commonly softened by curvature at both crest and toe, and rarely conform to one of the idealized profiles. PD 6688-1-4 acknowledges the difficulty, and offers in its Figure 2 an elaborate transformation procedure which involves plotting the ground profile up to 8 km upwind.

SCI recommends instead that attention be concentrated on the immediate vicinity of the site, where the equivalent slope should be estimated generously (i.e. as the steepest sustained gradient on any radial line within the sector). Unless the ground continues to fall away at a similar slope, the radius of interest need not extend further than a kilometre or two. The base level may not be easy to define, but a search radius of up to 4 km within the sector seems appropriate. The summit level will usually be more obvious, but it may be safer to underestimate this if the site is part way up. If the site lies downwind of an indistinct crest, it may be safer to underestimate the distance X which separates them. A particularly confused landscape might demand an element of trial and error, taking more than one idealized profile forward as far as Stage 17 in order to be confident that the worst case has been identified.

Stage 14 For each sector, derive the orographic location factor s

Once an equivalent idealized landform has been arrived at, orographic calculation is a relatively mechanical process.

The orographic location factor s is an intermediate parameter that is the same as in BS 6399-2 (though renamed from topographic location factor, and used differently). The graphs of EN 1991-1-4 Figures A.2 and A.3 are less helpfully presented than Figures 9 and 10 of BS 6399-2, and they exclude buildings which are low relative to the landform ($z < 0.1L_e$). However it is not necessary to consult the graphs, because algebraic expressions (A.4) etc. are available in lieu. A simplified re-presentation of these expressions follows.

The graphs are worth studying, nevertheless. They give a visual indication that orographic effect is most severe for a site on the crest, or slightly downwind in the case of a cliff or escarpment. Although orography is ignored at a site outside the 'danger zone' of Figure 5.13, the graphs extend well beyond these bounds. A NOTE acknowledges that orographic consideration outside the 'danger zone' is 'optional'. In this Design Guide the presumption is that designers will accept this and other opportunities to avoid it.

Downwind of a cliff or escarpment, the orographic 'danger zone' is not escaped until X exceeds $1.5L_e$. This distance (equal to the greater of $5H$ and $1.5L_u$) could extend well back from the crest. For the downwind portion of the graph, the abscissa is X/L_e, as opposed to negative X/L_u for the upwind portion.

It is also evident from the graphs that the orographic location factor s, and hence c_o, varies with z, so depends on the building as well as its 'orographic location'. In marginal cases, it is therefore possible for a location to be deemed 'orographic' for a low building but not for a taller one, or even vice versa (if downwind of an escarpment).

For the calculation of s by means of the algebraic expressions:

z	is the height of the building (or element for which the wind is being calculated) above local ground level
H	is the height of the orographic feature (hill or cliff up which the wind is blowing), whose extent on plan is:

L_u = H/ϕ

L_e is the greater of L_u and (with $\phi > 0.3$) $3.33H$. L_e is used to represent the scale of the landform

X is the horizontal distance between the building and the crest, in either direction. X is negative for a site on the upslope, zero at the crest and positive beyond it.

L_d need only be evaluated if:

i. the upwind slope is gentle ($\phi < 0.3$)
ii. there is a pronounced downwind slope ($\phi_d > 0.05$) and
iii. the building is actually located behind the crest, on that downslope.

If all these circumstances apply, the downslope is idealized as a constant slope whose extent on plan:

L_d = H/ϕ_d if the downslope extends down to (or beyond) base level; proportionately less if it does not.

For a tall building on a relatively trivial hill,

If $z > 2L_e$, the situation is deemed 'non-orographic' ($s = 0$)

For a site on the crest (of any orographic feature),

s = A (not to be confused with altitude)

$$= 0.1552(z/L_e)^4 - 0.8575(z/L_e)^3 + 1.8133(z/L_e)^2 - 1.9115(z/L_e) + 1.0124$$

For a site on the upslope (more than half way up),

$$s = Ae^{(BX/L_u)}$$

in which A is defined above, and

$$B = 0.3542(z/L_e)^2 - 1.0577(z/L_e) + 2.6456$$

For a site on the downslope of a hill or ridge,

$$s = Ae^{(BX/L_d)}$$

in which A is defined above, and

$$B = -0.3056(z/L_e)^2 + 1.0212(z/L_e) - 1.7637$$

For a site downwind of a cliff or escarpment,

$$s = A\,[\mathrm{Log}(X/L_e)]^2 + B\,\mathrm{Log}(X/L_e) + C$$

in which (**not** as above)

$$A \quad = -1.342\,[\mathrm{Log}(z/L_e)]^3 - 0.8222\,[\mathrm{Log}(z/L_e)]^2 + 0.4609\,\mathrm{Log}(z/L_e) - 0.0791$$

$$B \quad = -1.0196\,[\mathrm{Log}(z/L_e)]^3 - 0.891[\mathrm{Log}(z/L_e)]^2 + 0.5343\,\mathrm{Log}(z/L_e) - 0.1156$$

$$C \quad = 0.803\,[\mathrm{Log}(z/L_e)]^3 + 0.4236[\mathrm{Log}(z/L_e)]^2 - 0.5738\,\mathrm{Log}(z/L_e) + 0.1606$$

unless $z < 0.1L_e$ in which case (z/L_e) is taken as 0.1
[whence $\mathrm{Log}(z/L_e) = -1$, $A = -0.0202$, $B = -0.5213$, $C = 0.355$]

or $X < 0.1L_e$ in which case calculate for $(X/L_e) = 0.1$, calculate again for a site on the crest (topmost expression above), and interpolate.

Stage 15 For each sector, calculate the orography factor c_o

The orography factor is given by:

For slopes up to $\phi = 0.3$

$$c_o \quad = 1 + 2s\phi$$

For slopes $\phi > 0.3$ (i.e. a cliff)

$$c_o \quad = 1 + 0.6s$$

At this stage any sector with an orography factor less than 1.05 may be reclassified as ‘non-orographic’. In this event, skip Stages 16 and 17 for the sector(s) in question.

For completeness, it should be mentioned that an orography factor could also apply where wind ‘funnels’ into a valley whose sides are steep and convergent. There are no design rules in the Standard to derive an appropriate c_o (nor, for that matter, to quantify the beneficial sheltering effect in sectors not aligned with the valley). If a sector in line with the valley seems liable to govern, specialist advice may be called for.

Stage 16 For each sector, recalculate the altitude factor for the orographic base level

The altitude factor is recalculated using the same expression as at Stage 2, substituting a lower altitude, that of the foot of the hill or cliff, but still using the same value of z_s. The foot of the hill is the base level of the idealized slope assumed at Stage 13. This altitude is liable to vary from sector to sector.

The recalculated, smaller, ‘orographic’ altitude factor $c_{\mathrm{alt(o)}}$ will apply in conjunction with an orography factor c_o greater than 1. In practice, this means 1.05 and above, as lesser values will have been eliminated at Stage 15. Whenever c_o is taken as 1, the original c_{alt} from Stage 2 applies.

Stage 17 For each sector, calculate the 'orographic' peak velocity pressure for comparison with the 'non-orographic' q_p from Stage 11

The 'orographic' peak velocity pressure is given by:

$$q_{p(o)} = q_p[(c_{alt(o)}/c_{alt})(c_o + 0.6)/1.6]^2$$

It is possible for the reduction factor $(c_{alt(o)}/c_{alt})^2$ to outweigh the magnification factor $[(c_o + 0.6)/1.6]^2$, with the perverse effect that the orographic calculation produces a less onerous result.

Take the larger of the 'non-orographic' value (from Stage 11) and the 'orographic' value from this stage for the calculation of forces and surface pressures.

5.4 Calculation of overall force

Stage 18 For each sector, determine the size factor c_s

This may be obtained from Table 5.1 for the size factor zone (A, B or C) assigned at Stage 10.

Table 5.1 is based on Table NA.3 but has been rearranged zone by zone for ease of interpolation.

Size factors will depend upon the purpose of the wind calculation. For calculation of overall wind action for frame design, b and h mean, as usual, the breadth (cross-wind dimension) and height of the building as a whole.

For a typical rectangular building, size $(b + h)$ will differ from one principal direction to another. It is customary, and conservative, to take b as measured face-on for the nearest principal direction, though nothing in the NA would rule out a projected breadth (between diagonally opposite corners, as in Figure 10 of the PD) for a non-orthogonal sector. Other directional influences, potentially leading to variations in size factor between sectors, are zoning and displacement.

Strictly speaking, a size factor established for the building as a whole is only valid for the calculation of base shear and overturning moment. Calculation of the corresponding effects part way up a multi-storey building would theoretically call for a slightly larger size factor based on a smaller $(b + h)$. As a numerical example, consider a building 50 m high and 20 m wide in Zone B, without displacement. Table 5.1 gives a size factor of 0.9 for this building as a whole. But if brace member forces 30 m up the building are under investigation, only wind on the top 20 m is responsible for these effects. $(b + h)$ becomes 40 m and the size factor increases slightly to 0.92. In practice, unless the building is exceptionally tall, it is normally considered reasonable to overlook this complication and use the same storey forces throughout the frame design.

For portal framed buildings the usual design assumption is that lateral wind is resisted independently by each frame. For a typical (intermediate) frame, b can be taken as twice the bay width. (Stressed skin action, given suitable sheeting and attachments,

Zone A					
$b + h$ m	$(z - h_{dis})$				
	≤ 6 m	10 m	30 m	50 m	200 m
≤ 5	1	1	1	1	1
10	0.95	0.95	0.96	0.97	0.98
20	0.93	0.93	0.95	0.95	0.96
30	0.91	0.92	0.94	0.94	0.96
40	0.9	0.91	0.93	0.93	0.95
50	0.89	0.9	0.92	0.92	0.94
70	0.87	0.88	0.9	0.91	0.93
100	0.85	0.86	0.89	0.9	0.92
150	0.83	0.84	0.87	0.88	0.9
200	0.81	0.83	0.85	0.86	0.89
300	0.79	0.8	0.83	0.84	0.87

Zone B					
$b + h$ m	$(z - h_{dis})$				
	≤ 6 m	10 m	30 m	50 m	200 m
≤ 5	1	1	1	1	1
10	0.94	0.95	0.96	0.96	0.97
20	0.91	0.92	0.94	0.95	0.96
30	0.89	0.91	0.93	0.93	0.95
40	0.88	0.89	0.91	0.92	0.94
50	0.86	0.88	0.9	0.91	0.94
70	0.84	0.86	0.89	0.9	0.92
100	0.82	0.84	0.87	0.88	0.91
150	0.8	0.82	0.85	0.86	0.89
200	0.78	0.8	0.83	0.84	0.88
300	0.75	0.77	0.8	0.82	0.85

Zone C					
$b + h$ m	$(z - h_{dis})$				
	≤ 6 m	10 m	30 m	50 m	200 m
≤ 5	1	1	1	1	1
10	0.88	0.9	0.93	0.94	0.97
20	0.84	0.87	0.9	0.92	0.95
30	0.81	0.84	0.88	0.9	0.93
40	0.79	0.82	0.86	0.88	0.92
50	0.77	0.8	0.85	0.87	0.91
70	0.74	0.77	0.83	0.85	0.9
100	0.71	0.74	0.8	0.82	0.88
150	0.67	0.71	0.77	0.79	0.85
200	0.65	0.69	0.74	0.77	0.83
300	0.62	0.65	0.71	0.73	0.8

Table 5.1
Size factor c_s

could justify a larger dimension, but it would then become necessary to consider eccentric application; see Section 5.5.3.) For a portal frame whose span exceeds its height, with roof pressures predominant, the loaded area should be viewed on plan, taking $(b + h)$ in the size factor table as (span + 2 × bay width).

For a long building subdivided by movement joints, $(b + h)$ is assessed for each structurally independent portion.

For the calculation of wind effects on an isolated element such as an external column, $(b + h)$ represents the sum of the length and breadth of the element under consideration. For calculations of the effects of surface pressure on roof beams, cladding rails and the like, $(b + h)$ depends on the loaded area; see Section 6.1.2.

Stage 19 For each principal direction, determine the dynamic factor c_d

Not all buildings need to be treated as 'dynamic'. According to the NA (NOTE 4 to Figure NA.9) the dynamic factor c_d may be taken as 1 for buildings not exceeding 20 m in height with structural walls around lifts and stairs **and** 'additional masonry internal walls'. A few steel framed buildings may qualify for this exemption.

SCI recommends that **all** normal fully clad steel buildings up to 15 m in height may be considered non-dynamic, in view of the not inconsiderable stiffness offered by typical cladding and curtain wall systems. This concession could be extended to normal fully clad buildings up to 20 m in height whose lateral dimensions exceed $4h$.

Other steel framed buildings up to 20 m in height, unless furnished with both structural and masonry walls, will have to be assessed as dynamic, along with all buildings over 20 m.

For steel framed buildings in the 'dynamic' category, the dynamic factor c_d may be obtained from Table 5.2.

The dynamic factor depends on building proportions (h/b), so typically differs between the two principal directions of a rectangular building. A rectangular building is assigned a higher c_d with its narrow side to the wind than broadside on, which may seem counter-intuitive. It accounts for the slightly greater concentration of gust power over the smaller frontal area, and does not reflect any directional variation in the excitability of the structure as such.

For a long building subdivided by movement joints, b is the breadth exposed to the wind for each structurally independent portion. c_d may be taken as 1 for directions in which the portion is sheltered from the incident wind by another.

In EN 1991-1-4, damping is expressed as the logarithmic decrement of structural damping, δ_s, and informative Annex F suggests a value of 0.05 for typical steel buildings and 0.08 for 'mixed structures concrete + steel' which can be interpreted as composite construction and/or steel frame around a concrete core. Table 5.2 gives tables for both these values, prepared on the same basis as Figure NA.9.

$\delta_s = 0.05$						
h m	h/b 10	h/b 5	h/b 2	h/b 1	h/b 0.5	h/b 0.25
10	1.149	1.118	1.079	1.054	1.036	1.020
20	1.164	1.126	1.076	1.046	1.024	1.009
30	1.177	1.135	1.078	1.044	1.020	1.011
40	1.189	1.144	1.081	1.043	1.023	1.013
50	1.199	1.152	1.084	1.046	1.027	1.016
60	1.208	1.159	1.087	1.052	1.030	1.018
70	1.215	1.165	1.095	1.057	1.033	1.020
80	1.222	1.172	1.102	1.062	1.037	1.022
90	1.232	1.183	1.109	1.067	1.039	1.023
100	1.243	1.192	1.116	1.071	1.042	1.025

$\delta_s = 0.08$						
h m	h/b 10	h/b 5	h/b 2	h/b 1	h/b 0.5	h/b 0.25
10	1.111	1.089	1.058	1.039	1.022	1.009
20	1.113	1.087	1.050	1.027	1.010	1.005
30	1.118	1.089	1.047	1.022	1.012	1.007
40	1.123	1.092	1.047	1.025	1.014	1.008
50	1.128	1.095	1.049	1.029	1.017	1.010
60	1.133	1.098	1.055	1.032	1.019	1.011
70	1.137	1.105	1.060	1.036	1.021	1.012
80	1.145	1.112	1.065	1.039	1.023	1.013
90	1.153	1.119	1.070	1.042	1.025	1.015
100	1.161	1.126	1.074	1.045	1.026	1.016

Table 5.2
Dynamic factor c_d for $\delta_s = 0.05$ and 0.08

Table 5.2, like the graphs in the NA, is based on simplifying assumptions which are reasonable for mildly dynamic buildings within the scope of this Design Guide. The NA suggests that more accurate values could be calculated from Expression (6.3) and Annex B of the Standard. However non-specialist designers are recommended to avoid the complexities of this approach by using Table 5.2.

Stage 20 Consolidate sectors into 90° quadrants centred on the faces of a building

At this stage, with all directional influences accounted for, it is opportune to consolidate smaller sectors into 90° quadrants centred on the faces of a building that is rectangular or treated as such.

If the sector orientation was chosen to suit the building, the quadrant and sector boundaries will align. With each quadrant comprising three sectors of 30°, the greatest of three values of $q_p c_s c_d$ (or $q_{p(o)} c_s c_d$) is taken. If the alignment is not exact, the quadrant will encompass four 30° sectors; it will then be necessary to take the greatest of four values.

The size and dynamic factors both depend on b, so (unless the building happens to be square) sectors which straddle a quadrant boundary have to be subdivided to calculate a different $q_p c_s c_d$ for each quadrant's sub-sector. If tempted to avoid this complication by consolidating into face-centred quadrants prior to Stage 18, bear in mind that a size factor which is to be on the safe side for the quadrant as a whole must be based on the lowest displacement [highest $(z - h_{dis})$] and 'lowest' zone [A, B or C] from all the sectors wholly or partly embraced by that quadrant.

The following stages continue with the calculation of overall lateral force by means of a force coefficient.

Force coefficients are simple to apply but there is a less direct alternative route to overall design actions. Traditional vectorial summation of surface pressures is a valid alternative in all cases except where $h > 5d$, and can take account of surfaces which are inclined to the wind. For a multi-storey building, a force coefficient from Table 5.3 will generally be advantageous. However the pressure coefficient approach is appropriate for a low building with a pitched roof generating a significant portion of the wind action.

If calculating overall wind force by means of vectorial summation, exit the procedure at this stage. Turn to Section 6, but return to Stages 22/23 in case friction is significant.

Stage 21 Calculate the force acting on the building, quadrant by quadrant

The wind force is given by:

$$F_w = q_p\, c_s\, c_d \times c_f \times A$$

In this formula, c_f is a force coefficient, obtained either from Table 5.3 (which is derived from the NA) or from EN 1991-1-4, 7.6. A is normally the shadow area A_{sh}, which is bh if the roof is flat.

The NA presents its users with force coefficients (for cuboid buildings of height up to $5d$) under the guise of 'net pressure' coefficients in NA.2.27 f. This type of 'net pressure' coefficient is nearly but not quite the same as a force coefficient, mainly because it is subject to reduction by the lack-of-correlation factor noted in EN 1991-1-4, 7.2.2(3) (c_{loc} in Table 6.2 of this Design Guide). The other difference is that net pressure coefficients never include friction whereas force coefficients may or may not allow for it.

A true force coefficient can be derived as the product of the 'net pressure' coefficient from the NA and the lack-of-correlation factor. This friction-exclusive force coefficient is presented in Table 5.3.

Table 5.3 contains sufficient rows to allow linear interpolation between them, but if preferred the formulae are:

For h/d between 0.25 and 1,

$$c_f = 0.935 + 0.1839\ \mathrm{Ln}(h/d)$$

For h/d between 1 and 5,

$$c_f = [0.8125 + 0.0375h/d][1.1 + 0.1243\ \mathrm{Ln}(h/d)]$$

For $h/d > 5$, force coefficients are to be found in EN 1991-1-4, 7.6. These are derived for 'elements' but may be used for buildings. Indeed there is no alternative, other than the wind tunnel, as Table 7.1 of the Standard does not extend beyond $h/d = 5$. (Such slender buildings are in a minority and are not considered in detail in this Design Guide, but see Section 8.)

It is less clear whether EN 1991-1-4, 7.6 force coefficients were intended to be available below $h/d = 5$ alongside other approaches (Table 5.3 of this Design Guide or vectorial summation). The Standard does not explicitly rule in, but nor does it rule out the use of the 'element' coefficients with $h/d \leq 5$. An acute influence of plan proportions may be observed in EN 1991-1-4 Figure 7.23, so it is inevitable that there will be some mismatch with Table 5.3 force coefficients which depend only on h/d. In most cases the latter will be advantageous, as well as simpler to use.

EN 1991-1-4 Figure 7.23 coefficients ($c_{f,0}$ for members without free-end flow) need to be reduced by end effect factor ψ_λ (from EN 1991-1-4 Figure 7.36) when used on buildings. They may be further reduced by ψ_r (from EN 1991-1-4 Figure 7.24) if the building has rounded corners and is square (or nearly square).

For the simple example of a square building with $h = 5d = 5b$, the force coefficient of 1.46 obtained using EN 1991-1-4, 7.6 compares with 1.3 given in Table 5.3 of this Design Guide. However, a corner radius of $0.05b$ or greater could make the EN 1991-1-4, 7.6 approach attractive.

h/d	FORCE COEFFICIENT c_f (FRICTION EXCLUDED)
>5	Use EN 1991-1-4 Figures 7.23 and 7.36
5	1.3
4	1.23
3	1.15
2.5	1.1
2	1.05
1.5	1
1.2	0.96
1	0.94
0.9	0.92
0.8	0.89
0.7	0.87
0.6	0.84
0.5	0.81
0.4	0.77
0.35	0.74
0.3	0.71
≤ 0.25	0.68

Table 5.3 Force coefficients for cuboid buildings of height up to $5d$

If friction is **not** small enough to be ignored (see Stage 22), it must be calculated (Stage 23) and added.

For cylindrical and (regular) polygonal buildings, EN 1991-1-4, 7.9 and 7.8 respectively may be used. Note that for polygonal buildings b is defined as the diameter of the enclosing circle (as illustrated in EN 1991-1-4 Figure 7.26), which can make A (in the expression for F_w) somewhat larger than the shadow area.

In end effect calculations, a warning is in order: NA.2.44 states that EN 1991-1-4 Table 7.16 'should not be used', and stipulates different λ values in Table NA.10. For a regular (prismatic) building, this will give $\lambda = 4h/(bc_{f,0})$, and the line for $\varphi = 1$ on the graph in EN 1991-1-4 Figure 7.36 will be appropriate.

Stage 22 Consider whether friction is significant

In each principal direction, apply the test from EN 1991-1-4, 5.3(4): is the total area of surfaces parallel with the wind less than four times the total area of surfaces perpendicular to it?

For a cuboid building, this can be re-expressed as: is swept area $d(b + 2h)$ less than eight times shadow area bh?

If so, friction may be ignored. Proceed to Stage 24.

For surfaces which are neither parallel nor perpendicular to the wind, some judgement is called for. As recognized in the Standard, swept area need not be truly parallel to generate friction, but the 'small angle' referred to is not defined. SCI suggests that surfaces within 20° of the wind direction should count as swept. It is obviously safer to err on the generous side in the quantification of swept area.

The effect of this dispensation in practice is that friction will only need to be evaluated for shed-type buildings (and only in their long directions) but these exceptional cases need to be recognized.

In principle, friction may also be ignored if the force coefficient already allows for it. In practice, it is unlikely that friction-inclusive force coefficients would be used for the type of building whose friction is deemed significant according to the test above.

There is no compulsion to ignore friction. Voluntary submission to Stage 23 might be considered for (e.g.) a low building with a standing seam roof that is highly frictional in one direction.

Stage 23 Calculate the frictional force F_{fr} (where significant)

The frictional force is given by:

$$F_{fr} = c_{fr}\, q_p\, A_{fr}$$

in which $q_{p(o)}$ may substitute for q_p in an orographic situation.

A_{fr} is the frictional area. Observe that A_{fr} is less than the full swept area. As illustrated in EN 1991-1-4, Figure 7.22, friction is not considered to act on a zone of detachment nearest the upwind end, whose horizontal extent is the smaller of $2b$ and $4h$.

It may be worthy of remark that EN 1991-1-4 does not apply size and dynamic factors to friction, if this is calculated separately (whereas friction included in a force coefficient will be subject to these factors).

The coefficient c_{fr} (prescribed normatively in EN 1991-1-4 Table 7.10) varies between 0.01 for a smooth surface and 0.04 for one which is ribbed, corrugated or has standing seams across the direction of flow. For ribs or corrugations in line with the flow, the profile geometry could be considered to increase the area of smooth surface at $c_{fr} = 0.01$.

It is advisable to keep separate account of friction at walls and roof, so that any difference in the smoothness of the roof and wall surfaces can be allowed for and horizontal bracing design forces can be correctly evaluated.

Stage 24 For each quadrant, calculate the overall force

The overall lateral wind force on the building is the sum of F_w and F_{fr} from Stages 21 and 23 respectively.

If friction was deemed insignificant at Stage 22 (or included in the force coefficient) the overall wind force is simply taken as F_w.

The same symbol, F_w, is used for the resultant wind force and its (majority) non-frictional component. This may arise from the presumption, noted in EN 1991-1-4, 7.1.1(4), that force coefficients include friction 'if not specifically excluded'. The ambiguity is one to be aware of, as friction is not always included and can be significant. Note in particular that the recommended force coefficients in Table 5.3 of this Design Guide are friction-exclusive.

Stage 25 For each of two orthogonal directions (e.g. N-S and E-W), quote the overall force as a ± value

Stage 25 is optional. The four quadrants can be further consolidated into two orthogonal directions, for each of which the wind force is quoted as a ± value, the greater of the two opposite quadrants. This is appropriate if the lateral force resisting system will have the same resistance in opposite directions. With unsymmetrical bracing patterns it can be advantageous to retain the four lateral forces from Stage 24 and verify separately for each.

At the conclusion of the procedure a reminder may be in order: these forces are characteristic. Design forces are obtained by factoring characteristic values as discussed in Section 7.

5.5 Application of lateral wind force to the building

5.5.1 Apportionment by level

The overall wind force, calculated using the force coefficient, gives the base shear that the steel frame or its bracing system must be designed to resist. It is customary to make the somewhat sweeping assumption that the force is uniformly distributed among the storeys and the overturning moment is equal to the base shear times half the height. For irregular storey height, the force is apportioned pro rata to tributary area. If ‘division by parts’ (permitted, but not encouraged; see Section 6.4) were used, storey forces would vary and the moment would turn out somewhat greater than $Fh/2$.

In reality, storey forces vary in a more complex manner than ‘division by parts’ (as illustrated in EN 1991-1-4 Figure 7.4) would predict; the gradual increase in front face pressure with height is not replicated at the rear and the topmost stories benefit from easing due to the end effect. In practice these complexities, and the size effect differential mentioned at Stage 18, are rarely explored, but they may be borne in mind when downsizing columns and other members of the bracing system at intermediate levels.

5.5.2 Interacting bracing systems

Conventionally, the wind forces from the two orthogonal directions are designed against independently. However, orthogonal bracing systems may have columns in common. If so, an intermediate wind direction could govern the design of these members and their connection to the ground. As a simple example, the design force in the leg of a square lattice tower (whose wind force is similar in all directions) is 40% greater with wind on the diagonal than face-on. It is clearly not sufficient, in a member which participates in resisting wind from both principal directions, to consider them to act singly. In this tower leg example, application of 70% of each principal direction’s wind force in combination would be equivalent in effect to the wind at 45°. In a less symmetrical structure, 70% may not be enough, but 80% (as suggested in PD 6688-1-4, 2.9) might be over-conservative. Alternatively, but tediously, directional coefficients (Table 4 of the PD) might be employed to calculate, for 15° increments of wind direction, a resultant force (generally neither concentric nor in line with the wind).

5.5.3 Eccentric application

Maximum lateral force, applied centrally, represents the most onerous design situation if lateral resistance is widely dispersed, but this is not always the case. With lateral resistance concentrated (e.g. in a single central core) an off-centre application of part of the force, causing a twisting effect, could represent a more demanding design situation than a centrally applied force. NA.2.23, countermanding EN 1991-1-4 Figure 7.1, prescribes, in effect, that 65% of the design wind force applied at a horizontal eccentricity of $b/6$ should be considered as an alternative to 100% applied centrally. SCI recommends that this provision need not be applied to a portal framed shed-type building for which the size factor was based on no more than two bay widths.

SURFACE PRESSURES

The force coefficient approach, generating overall wind forces directly, has been given precedence in this Design Guide because it will be advantageous to use force coefficients from Table 5.3 of this Guide for the structural design of most buildings. A force coefficient should, in principle, generate a more accurate – and smaller – design force for this purpose than the alternative vectorial summation of surface pressures.

Vectorial summation (calculation of pressure, and hence force, on all contributory wall and roof surfaces and adding their horizontal components in the wind direction, together with friction where significant) is familiar to users of BS 6399-2. It remains appropriate for buildings whose pitched roofs generate a significant portion of the wind action, notably portal frames. For most other buildings, vectorial summation has not been ruled out but is unlikely to be as productive as the force coefficient approach described in Section 5 (Stage 21) – even if the building is tall enough for 'division by parts' as illustrated in EN 1991-1-4 Figure 7.4 and discussed in Section 6.4. (For very slender buildings with $h > 5d$, vectorial summation **is**, in effect, ruled out, because of the validity limitation noted under Table 6.1.)

Although the Standard embraces a variety of roof shapes, the buildings under them are generally assumed to be rectangular. This is not always the case in practice. For irregular outlines and setbacks, designers may turn to the PD for NCCI, which is based on pressure coefficients and vectorial summation.

Irrespective of the approach taken to calculate the overall wind action, it will always be necessary to evaluate surface pressures, both external and internal, for purposes such as the design of cladding and the members which support it.

In principle, pressures acting on a surface are calculated as:

$$w = q_p \, c_s \, c_d \times c_p$$

in which c_p is the relevant pressure coefficient (c_{pe} for an external surface, c_{pi} for internal). Velocity pressure q_p is as calculated in Stage 11, but substituted by $q_{p(o)}$ from Stage 17 if higher.

For an overall force calculation, the procedure described in Section 5 should be followed to Stage 20 at which the highest value of $q_p \, c_s \, c_d$ from all the sectors wholly or partially included within a quadrant 45° either side of the direction normal to the face is taken.

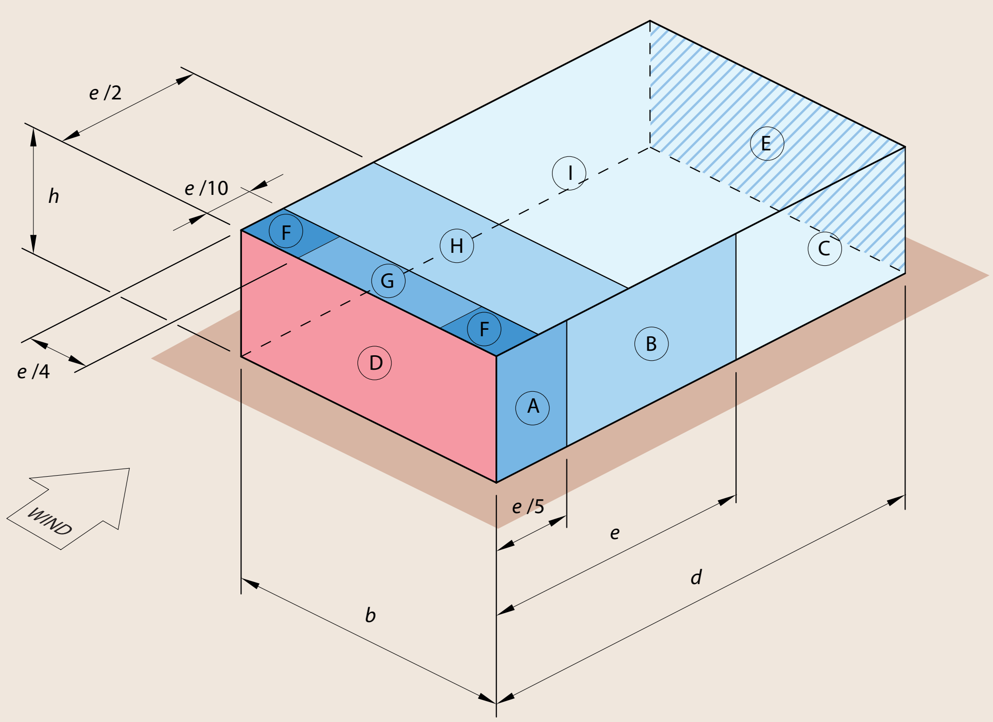
For **local** pressure calculations, c_s and c_d will differ from those used in the overall force calculation (see Sections 6.1.2, 6.2.3 and 6.3.1). In a local pressure calculation, c_d will usually be taken as 1 and c_s may conservatively be taken as 1.

6.1 External pressure coefficients

All of the external pressure coefficients (c_{pe}) in EN 1991-1-4, 7.2 are now identified for national determination, and virtually all of the Recommended Values (except those for domes) are substituted by nationally determined values in the 2010 revision of the NA. The Standard offers two pressure coefficients, one for loaded areas of 1 m^2 and below and a lower one for loaded areas of 10 m^2 and above, with logarithmic interpolation between the two. The NA sets the 1 m^2 values equal to the 10 m^2 values – effectively a declaration that size effect is adequately accounted for by size factor alone. For buildings in the UK there is, in fact, only one set of external pressure coefficients (though it should be noted that for some surface zones ‘most positive’ and ‘most negative’ values are given).

Table 6.1, which is an expanded version of Table NA.4, gives pressure coefficients for the walls of rectangular-plan buildings.

For roof pressure coefficients, reference should be made to Tables NA.5, 6, 7 and 8. Many variations of roof shape and eaves treatment are covered in the NA. These include vaulted (barrel) and domed roof surfaces, for which reference should be made to NA.2.29.



Zone extent parameter e is the smaller of b and $2h$

Note that a downstream zone will not exist if the building comes to an end within its predecessor

Figure 6.1
Key to pressure zones for a cuboid building

SIDE ZONES			FRONT	REAR	h/d
A	B	C	D	E	
−1.2	−0.8	−0.5	+0.8	−0.7	5
				−0.65	4
				−0.6	3
				−0.55	2
				−0.5	1
			+0.77	−0.45	0.8
			+0.75	−0.39	0.6
			+0.73	−0.37	0.5
			+0.72	−0.34	0.4
			+0.71	−0.31	0.3
			+0.7	−0.3	≤0.25

Table 6.1 Wall pressure coefficients for a rectangular building

Note: No pressure coefficients are available for $h/d > 5$, except that for cladding pressure (only) NA.2.27 permits use of the values for $h/d = 5$ 'in the absence of better test data'.

Zones are defined in Figure 6.1 for the walls of all rectangular buildings (for use with Table 6.1, or Table NA.4), and for a flat roof (for use with Table NA.5). For eaves variations and pitched or hipped roofs, subdivisions or additional zones are introduced, for which key diagrams in one document (EN 1991-1-4 Figures 7.6 onwards) must be referred to alongside the Tables in another (the NA).

For vaulted and domed roofs, zone designations A, B and C are differently redefined in EN 1991-1-4 Figures 7.11 and 12. These should not be confused with wall Zones A, B and C, nor with size factor zones, nor with one another.

6.1.1 Lack of correlation

A NOTE to EN 1991-1-4, 7.2.2(3) prescribes a factor to account for lack of correlation between peak front and rear face pressures on buildings. In this Design Guide the symbol c_{loc} is used for this factor, which is set out in Table 6.2. It is slenderness dependent; only relatively stocky buildings receive the full benefit, and the most slender do not benefit at all. (In contrast, BS 6399-2 permitted a factor of 0.85 regardless.)

h/d	c_{loc}
≥ 5	1
4	0.96
3	0.93
2	0.89
≥ 1	0.85

Table 6.2 Factor c_{loc} for lack of correlation
(Source: EN 1991-1-4, 7.2.2(3) NOTE)

NA.2.19 makes it clear that c_{loc} applies to the horizontal component of wind action on a sloping roof, as well as the front and rear walls. It is not applicable to the vertical component, so designers of portal frames may judge it expedient to apply c_{loc} to the wall pressures only.

6.1.2 Size and dynamic factors

In principle, the effects of external pressure are subject to both size factor c_{s} and dynamic factor c_{d} and these will depend on the effect being designed against.

Overall lateral forces, however derived, are factored by $c_s c_d$, as described in Section 5 (Stages 18 and 19). These factors are based on the overall dimensions of the building (irrespective of any 'division by parts').

Size and dynamic factors thus obtained are inappropriate for more local calculations such as for a member which supports cladding. The size factor is always based on the dimensions of the area whose wind increases the effect being designed against.

For a member such as a roof beam, $(b + h)$ in Table 5.1 is the sum of the length and width of the area whose incident wind adds to its bending moment. Note that this loaded area is not the same as tributary area. It will often be convenient to regard it as the area which would become unsupported in the absence of the member or connection under design, but any area whose wind counters the effect in question needs to be excluded.

Normally, c_d is taken as 1 for local pressure calculations. In principle, however, any portion of structure which is dynamic enough to need one should have its own c_d, estimated from first principles. A stadium roof might be a case in point.

6.2 Internal pressure

Internal pressure can usually be ignored in the calculation of overall lateral forces, as pressures on opposite faces balance out. This is convenient because internal pressure can vary over a considerable range from positive to negative, depending on the permeability of the faces (relative to one another) and their external pressures.

Overall lateral design forces can, however, come under the influence of internal pressure where a long building is subdivided by one or more movement joints into structurally independent portions, or where the ground level differs between opposite faces.

Evaluation of internal pressure is also important in a roof uplift situation, with maximum positive internal pressure countered by unfactored self weight. In another design situation, negative internal pressure might combine unfavourably with gravity loading and/or positive external pressure.

EN 1991-1-4, 7.2.9(6) notes that in the absence of a dominant opening the internal pressure coefficient (c_{pi}) may be taken as the more onerous of +0.2 and −0.3.

6.2.1 Portal frames

For portal frame design, there is an economic imperative to quantify internal wind pressure more precisely. Positive internal pressure is unfavourable for rafters and connections in the wind uplift design situation. Since the surface area exposed to negative external pressure will usually be much greater than that exposed to positive, a calculation based on EN 1991-1-4, 7.2.9(6) should be able to justify an internal pressure coefficient well into the negative, unless the windward wall is disproportionately permeable. With all faces equally permeable, the windward face would have to exceed 19% of the total surface area for the internal pressure coefficient to be less negative than −0.2.

For buildings in which all faces are **not** equally permeable, the 'balance of airflow' method (Appendix C of SCI Publication P286[15]) remains valid.

6.2.2 Dominant openings

A dominant opening (such as an open door or broken window) would upset any such sensitive calculation, as internal pressure can attain 75 to 90% of that outside the opening. If it is necessary to allow for it, an unintentional dominant opening should be treated as an accidental design situation with reduced partial factors; see Section 7.3 of this Design Guide. PD 6688-1-4, 2.15 suggests a more cautious approach in some cases (a fire station appliance bay or a military hangar, perhaps).

EN 1991-1-4, 7.2.9(4) defines as 'dominant' a face in which dominant opening(s) plus regular leakage exceed twice the area of regular leakage in the other faces. In an otherwise well sealed building, any open door, or even window, is liable to create a dominant face. EN 1991-1-4, 7.2.9(5) prescribes how c_{pi} is to be interpolated between $0.75c_{\mathrm{pe}}$ and (with three times more area in the dominant face) $0.9c_{\mathrm{pe}}$, in which c_{pe} is the external pressure coefficient at the location of the dominant opening.

For a dominant opening on a windward face, EN 1991-1-4, 7.2.9(7) implies that internal pressure may be based on a reduced peak velocity pressure q_{p}, recalculated with z to the top of the door or window at risk.

6.2.3 Size and dynamic factors

It is clear from EN 1991-1-4 Expression (5.6) that size (and dynamic) factors are not intended to apply to the effects of internal pressure. This is contrary to traditional UK practice, but there is no provision for national choice.

6.3 Pressures for cladding design

For cladding design purposes, the worst case will typically be the combination of high local suction externally with maximum internal pressure. It may also be necessary to evaluate the combination of positive external pressure with maximum internal suction, but this is unlikely to be as severe (numerically at least).

It would be legitimate to recalculate the wind with altitude factor based on z_{s} for the topmost panels, but simpler to retain q_{p} (or $q_{\mathrm{p(o)}}$) as previously calculated for structural design purposes with $z = h$ and $z_{\mathrm{s}} = 0.6h$.

It would **not** be legitimate (except for positive pressure on the windward face) to recalculate the wind for z lower than the top of the building. On the three walls subject to suction, NA.2.26 requires the pressure distribution to be assumed to be uniform over the whole height, rejecting any notion (in the NOTE to EN 1991-1-4, 7.2.2) that an individual project might define its own rules. In practice, cladding is usually made the same at all levels and designed for the highest pressure.

6.3.1 Size and dynamic factors

For a cladding panel in the UK, the dynamic factor c_d does not apply. The NA (in NOTE 4 to Figure NA.9) grants an exemption for all cladding panels and elements, despite a suggestion in EN 1991-1-4, 6.2(1)b that a cladding panel whose natural frequency is less that 5 Hz ought to be treated as dynamic.

For a cladding panel, $(b + h)$ for size factor purposes is the sum of the breadth and height of the panel. Large panels (whose dimensions add up to more than 5 m) would qualify for $c_s < 1$ (for the external pressure only), but it is always safe to ignore size effect and take $c_s = 1$.

The same applies to non-panelized cladding systems. In principle size factors could be calculated, individually, for any members of the cladding system that support large areas of facade or roof.

The size factor is always based on $(b + h)$ equal to the sum of the sides of the notionally (if not actually) rectangular area whose incident wind is additive to the effect being designed against.

It follows that if there is a cantilever (which would be subtractive) its area needs to be excluded when the midspan bending resistance of the member is verified. A different size factor would apply for verification of the cantilever itself, and potentially yet another for an attachment to the building frame (at which both areas are additive). All such complication is avoided by taking $c_s = 1$.

6.3.2 Funnelling

A point to watch for in relation to cladding design is the possibility of increased suctions on side faces where wind is funnelled between buildings (see notes under Table NA.4). The effect is at its worst when the gap between the buildings is $0.5e$, where e is the zone extent parameter (see Figure 6.1) for the smaller of the two buildings.

6.3.3 Orographic situations

Another potential complication is that in some orographic situations it is possible for the peak velocity pressure to be higher part way up than at the top. A high building on a (relatively) low hill or cliff can rise above the most intense orographic effect, as indicated in EN 1991-1-4 Figure A.1. This is one situation in which $q_{p(o)}$ for the top of the building might be on the unsafe side for cladding verification.

6.3.4 Corner suctions

Cladding design is commonly governed by high local suctions near corners. If the corners are not square, the Zone A pressure coefficient of −1.2 is unduly onerous. Reductions are offered by the PD in its Table 5, but note that these apply to its immediately preceding Table 4 in which the most negative value of c_{pe} is −1.3, not −1.2 as in Table NA.4 (and Table 6.1 of this Design Guide).

6.4 Division by parts

'Division by parts' is the traditional practice of calculating velocity pressure separately for successive 'slices' of the building, to take account of the variation of wind speed with height. While this is appropriate and advantageous for essentially linear structures such as masts and chimneys, the flow around buildings is different; it is only for positive pressure on the front face that the method is considered to be valid. For the entire rear face, and the sides, pressures must always be based on velocity pressure q_p as calculated for the top of the building. This stipulation reduces the advantage gained in return for considerable extra computational effort in recalculating q_p for the top of every part, taking account of differences in altitude factor, exposure (or roughness) factor and town terrain correction factor. Except for buildings of two distinct parts, such as a tower block on a podium (see PD 6688-1-4, 3.3), division by parts is not encouraged in this Design Guide. Simple and direct use of force coefficients from Table 5.3 is likely to give lower values.

Comparative example

Take for example a 90 m high building, 30 m square, located 20 km from the shoreline and 2 km into a town for which v_{map} is 22.5 m/s. This calculation is for the sector in which $c_{dir} = 1$ and displacement is taken as zero. Altitude factor variation will be avoided by assuming a site close to sea level so that $c_{alt} \approx 1$ regardless of height.

Force coefficient approach

At the top of the building, $c_e c_{e,T} = 3.9$ and $q_p = 1210$ Pa.

With a force coefficient of 1.15 (from Table 5.3 for $h/d = 3$), base shear is:

$$1.15 \times 1.21 \times 30 \times 90 = \mathbf{3.76\ MN}$$

and overturning moment is:

$$3.76 \times 90/2 = \mathbf{169\ MNm}$$

Both these effects are subject to $c_s = 0.88$ and $c_d = 1.13$, but it happens that the two factors cancel one another out in this example.

Division by parts and vectorial summation of surface pressure

Alternatively, consider the building divided into five parts, in accordance with EN 1991-1-4, 7.2.2(1). Pressure coefficients are +0.8 and −0.65 for Zones D and E respectively (from Table 6.1 of this Design Guide for $h/d = 3$).

For Part 1, the top 30 m,	$q_p = 1210$ Pa as before.
Front face force is	$0.8 \times 1.21 \times 30 \times 30 = 871$ kN, acting 75 m above ground.

For Part 2, a 10 m slice,	$z = 60$ m. $\quad c_e\, c_{e,T} = 3.67$ and	$q_p = 1139$ Pa.
Front face force is	$0.8 \times 1.14 \times 30 \times 10 = 273$ kN,	acting 55 m above ground.
For Part 3, a 10 m slice,	$z = 50$ m. $\quad c_e\, c_{e,T} = 3.54$ and	$q_p = 1098$ Pa.
Front face force is	$0.8 \times 1.1 \times 30 \times 10 = 264$ kN,	acting 45 m above ground.
For Part 4, a 10 m slice,	$z = 40$ m. $\quad c_e\, c_{e,T} = 3.38$ and	$q_p = 1049$ Pa.
Front face force is	$0.8 \times 1.05 \times 30 \times 10 = 252$ kN,	acting 35 m above ground.
For Part 5, the bottom 30 m,	$z = 30$ m. $\quad c_e\, c_{e,T} = 3.15$ and	$q_p = 977$ Pa.
Front face force is	$0.8 \times 0.98 \times 30 \times 30 = 704$ kN,	acting 15 m above ground.

The front face forces from the parts and their contributions to the overturning moment add up to 2.36 MN and 112 MNm.

The rear face force is $\quad 0.6 \times 1.21 \times 30 \times 90 = 1.96$ MN
and its overturning moment is $1.96 \times 90/2 = 88$ MNm.

Combining the front and rear faces and applying c_{loc} of 0.93 (from Table 6.2 for $h/d = 3$) gives an overall base shear of **4 MN** and an overturning moment of **186 MNm**. Size and dynamic factors (based on whole building dimensions, not those of the parts) are as above and do not influence the comparison.

Conclusion

In this fairly realistic numerical example, division by parts has failed to reward the designer for the computational effort expended. Indeed it has yielded results 6% and 10% **higher** than those obtained using the force coefficient from Table 5.3.

6.5 Multispan roofs

For 'multispan' roofs (with multiple ridges and valleys) special rules apply.

EN 1991-1-4 Figure 7.10 illustrates various multiple ridge-and-valley roof types, including the repeated duopitch of the typical multibay portal frame as well as the classic north light factory roof. Pressure coefficients are related to those for zones H and I of EN 1991-1-4 Table 7.4 or 7.3 as appropriate, except that for configuration b (north light roof with wind from the south) a pressure coefficient of −0.4 applies to every valley face. Valleys with the same pressure acting on both sides make no contribution to the vectorial summation, regardless of their number.

The possibility that vectorial summation might result in a horizontal component which is unrealistically small in relation to the roof area was recognized in the 2010 revision to the Standard. Consequently, EN 1991-1-4, 7.2.7(4) dictates a 'minimum horizontal force' – which may be given the symbol F_{shed} – of $0.05 q_p A_{shed}$ in which A_{shed} is the entire plan area of the multispan roof. The quasi-friction coefficient of 0.05 is described as a 'roughness factor', not to be confused with (terrain) roughness factor c_r.

Presumably F_{shed} can be assumed to act at ridge height, to replace regular friction on the upwards-facing friction area (though regular wall friction may still be significant) and to be subject, along with the force from front and rear walls, to lack-of-correlation factor c_{loc}.

DESIGN VALUES OF WIND ACTIONS

This Section is not a comprehensive review of its subject, but aims to draw attention to differences in the Eurocodes from traditional UK practice.

7.1 Classification

EN 1990 provides for actions to be classed as:

- Permanent or variable
- Direct or indirect
- Fixed or free
- Static or dynamic

Wind actions are classified in EN 1991-1-4, 3.3(1) as variable fixed actions, 'unless otherwise specified'. They are free in the sense that the wind can blow from any direction, but conventionally 'fixed' in orthogonal directions for structural analysis and verification. Likewise they are nothing if not dynamic, but are conventionally treated as quasi-static, with dynamic amplification factors. Most wind actions are 'direct', but internal pressure in a fully enclosed building is regarded as 'indirect'.

In EN 1990's terms, nearly all wind design situations are 'persistent' (relevant over the lifetime of the structure) not 'transient'. An example of a transient design situation would be verification of an unclad frame for a limited period in the course of construction (as discussed in Appendix B). The distinction is a subtle one, however, as persistent and transient design situations are factored alike in the NA to BS EN 1990[16] Table NA.A1.2(B) etc.

7.2 Partial factors on actions

The result of an evaluation in accordance with EN 1991 is a characteristic value. Design values of actions are obtained by multiplying characteristic values by partial factors and combination factors as appropriate.

Partial factors on actions are obtained from EN 1990 and its National Annex.

In a design situation in which wind force is the leading variable action, as for instance in an overturning calculation, the partial factor γ_Q is 1.5. The same factor applies to leading variable actions of all kinds.

In previous UK practice, a factor of 1.4 would have been applied to the wind force. In consequence, design overturning moments are increased 7% over previous values whereas the gravity loads which counter them are little changed. In verification for static equilibrium ('EQU'), the countering (favourable) gravity loads are multiplied by a partial factor γ_G of 0.9; for strength design ('STR') they are factored by $\gamma_{G,inf} = 1$. For example, to verify that a gravity base does not lift off the ground the 'EQU' limit state applies; the 'STR' limit state would apply to the column and its holding down bolts.

It has been suggested that the 7% increase might be viewed as an unofficial margin versus future climate change, an uncertainty the Standard does not address.

A lower overall factor applies to wind forces in combinations in which they are the accompanying variable action, as for instance in the calculation of maximum compressive force in a column which participates in a bracing system. Wind force is subject to a combination factor $\psi_0 = 0.5$, making an overall factor $(\gamma_Q \psi_0) = 0.75$. There is no ULS combination from which wind is excluded; unfavourably directed wind will contribute in some measure to the ultimate design compressive force in the column.

The value of combination factor $\psi_0 = 0.5$ for wind is a UK national choice, lower than EN 1990 Table A1.1's Recommended Value (which is 0.6), but in harmony with the Recommended Value for snow (up to an altitude of 1000 m).

It should be noted that equivalent horizontal loads (EN 1993-1-1,[17] 5.3.2) are **not** independent variable actions; they can be regarded as an inclination of the gravity loads and are factored as such. They can act in any direction, along with the wind.

Only actions that can apply simultaneously need to be considered in combination. On a roof, imposed load can normally be assumed absent when full design wind (or snow) acts. It is highly improbable that snow on an unobstructed roof could coexist with full design wind, but the combination of snow and wind might need to be considered where wind-blown snow can be redeposited at a valley, parapet or wall. For purlin design, the effect of most positive external pressure together with most negative internal would act in combination with that of snow. Wind and snow in turn would each be considered as the 'leading' (or 'main accompanying') variable action.

External and internal wind pressures are non-independent variable actions and therefore share a common factor even when countering one another (as where reliably negative internal pressure opposes high local suction outside).

7.3 Accidental design situations

EN 1991-1-4, 2(4) envisages certain circumstances (unintentional dominant openings) in which it is appropriate to treat wind action as 'accidental'; EN 1990 A1.3.2, which prescribes the partial factors and combination factors to be used in accidental design situations, would apply. In an accidental design situation, the accidental action is unfactored. Any coexistent permanent action (e.g. roof self weight) would also be unfactored. Any main, or single, accompanying variable action would be subject to combination factor ψ_1 given by Table NA.A1.1 of the UK NA to EN 1990 (e.g. 0.2 for snow). It is unlikely that more than one accompanying variable action would combine unfavourably with accidental wind.

7.4 Fatigue limit state

Wind resisting structures can be subject to fatigue, but buildings within the scope of this Design Guide are generally regarded as non-susceptible. Specialist advice is recommended where external elements may be at risk.


ONE SNOWHILL

TALL AND UNUSUAL STRUCTURES

This Design Guide is for the majority of buildings in the UK which do not require specialist wind engineering expertise. However, it may be helpful to discuss the circumstances in which specialist advice can be beneficial.

Wind tunnel testing is all but obligatory for the very highest towers. Indeed buildings over 200 m in height exceed the applicability limit declared in Clause 1.1 of the Standard. For many other tall buildings an investment in such testing is expected to yield a dividend in the form of lower design actions, superior serviceability performance and more accurate pressure predictions for cladding and mechanical design. It is not possible to declare that buildings above a certain height (say 100 or 120 m) would benefit; slenderness is at least equally important and specialist referral should be considered for a building whose height exceeds 5 or 6 times its lesser lateral dimension. A building whose fundamental frequency is liable to be below average (say $n_1 < 46/h$, where fundamental frequency n_1 is in Hz with height h in metres) would also be a candidate. Building shape is another relevant factor. A 3-dimensional mode of vibration, involving twisting, could demand study, as could a location with complex surrounding terrain or potential interference from other tall structures.

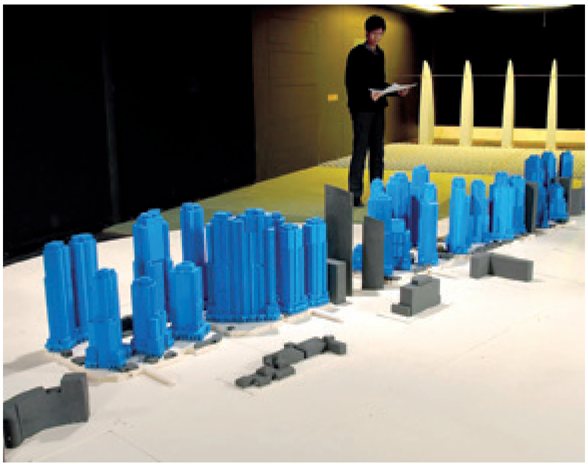


Figure 8.1
Wind tunnel testing
Courtesy of BMT Fluid Mechanics

Studies of 'environmental' wind at street level can also be undertaken in the wind tunnel.

Properly conceived and executed wind tunnel studies can give confidence in serviceability performance, and allow optimization of shape to minimize synchronized vortex shedding. Although irregular architectural outlines and changes of cross section can be challenging, their aerodynamic effect can be turned to advantage in this respect. Even without wind tunnel testing, an experienced wind engineer may be able to propose variations in building outline to reduce wind action and its adverse effects.

Wind forces derived from project-specific wind tunnel testing will almost always be lower than those predicted by standardized rules, giving potential for savings.

DESIGN EXAMPLE

9.1 Wind on a building (Sheffield Bioincubator)

The example building is Sheffield University's Bioincubator[18], located just over 100 m above sea level at 53°22'54"N/1°29'W, SK345873. The situation, on a bluff overlooking the city centre and the Don valley, looks potentially 'orographic'.

The Sheffield Bioincubator, shown in Figure 9.1, was the subject of trans-national Eurocode design comparisons under the auspices of the Leonardo da Vinci programme[19]. A conventional six storey office/laboratory building, steel framed with composite floors, it is rectangular on plan but for one inset corner with an isolated 21 m high column as an architectural feature. Overall dimensions are 29 × 20 × 27 m high. The wind will be evaluated for the enclosing cuboid without regard for setbacks at roof level and the inset corner. As the height does not exceed 50 m, the NA's simpler treatment is valid, whether or not orography is significant.

Figure 9.1
Sheffield Bioincubator from the south

This example uses the SCI Wind Calculation Sheet (Appendix C), which is designed for twelve 30° sectors oriented to suit a rectangular building. Each group of three sectors corresponds to a quadrant centred on a face of the building. The procedure of Section 5 is followed to arrive at the overall wind forces acting on the building. Numerical results are summarized in Figure 9.2, with orographic influence distinguished by the use of orange print.

For the purposes of this example, calculation results are presented for all sectors. In practice, an experienced designer would probably save effort by reviewing the results at Stage 11 and thereafter confining attention to sectors S9, S10 and S11.

Stage 1

From the wind map (Figure 5.1), Sheffield's map wind speed $v_{map} = 22.1$ m/s

Stage 2

For a 27 m high building at an altitude of 105 m, Altitude factor

$$c_{alt} = 1 + 0.001A[10/(0.6\ h)]^{0.2}$$

$$= 1 + 0.001 \times 105\ [10/(0.6 \times 27)]^{0.2}$$

$$= 1.095, \text{ say } 1.1$$

Stage 3

The building faces are oriented almost exactly N, S, E and W and sectors can be laid out to suit: sector S1 between 315° and 345°, S2 between 345° and 015°, S3 between 015° and 045°, and so on. At a later stage each group of three sectors will be consolidated into a face-centred quadrant, such that quadrant Q1 = [S1 + S2 + S3], Q2 = [S4 + S5 + S6], and so on.

Stage 4

Direction factor c_{dir} is obtained from Figure 5.3 of this Design Guide. For 30° sectors the value may be read on the centreline of the sector.

c_{dir} = 0.82 for S1, 0.78 for S2, and so on.

Stage 5

This is an urban site and it should be possible to take advantage of displacement. However, sectors S1, 8, 9, 10, 11 and 12 face a wide dual carriageway and a large roundabout with low density development beyond. It seems prudent not to count on any displacement effect from these directions, despite the presence of some quite high buildings in the middle distance (see Figure 9.3).

Figure 9.2 (Opposite) SCI Wind Calculation Sheet for Sheffield Bioincubator

SCI Wind Calculation Sheet

	SHEFFIELD BIOINCUBATOR (SK345873; 53°22'54"N / 1°29'W)													
1	Map wind speed v_{map}	22.1												m/s
	Height of building h	27												m
	Site altitude A	105												m
2	Altitude factor c_{alt}	1.1												
	Quadrant number	Quadrant 1			Quadrant 2			Quadrant 3			Quadrant 4			
	Sector number	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	
3	Sector orientation	315–345	345–015	015–045	045–075	075–105	105–135	135–165	165–195	195–225	225–255	255–285	285–315	°
4	Directional factor c_{dir}	0.82	0.78	0.73	0.73	0.74	0.73	0.8	0.85	0.93	1	0.99	0.91	
5	Displacement height (if any) h_{dis}	0	10	10	10	10	10	10	0	0	0	0	0	m
	$z - h_{dis}$ $(= h - h_{dis})$	27	17	17	17	17	17	17	27	27	27	27	27	m
6	Distance to shoreline	100	100	100	90	100	100	100	100	100	100	85	100	km
7	Exposure factor c_e	2.98	2.67	2.67	2.68	2.67	2.67	2.67	2.98	2.98	2.98	2.99	2.98	
8	Distance into town	4	5	4	5	5	2	3	4	4	2	2	3	km
9	Correction factor $c_{e,T}$	0.94	0.88	0.89	0.88	0.88	0.93	0.91	0.94	0.94	0.98	0.98	0.96	
10	Zone for size factor	C	C	C	C	C	C	C	C	C	C	C	C	
11	$q_p = 0.613(v_{map} \times c_{alt} \times c_{dir})^2 \times c_e c_{e,T}$	682	518	459	455	466	479	563	733	878	1058	1040	858	Pa
12	Potentially significant orography?	×	×	×	✓	×	×	×	×	×	×	×	×	
13	Upwind slope of hill Φ				0.055									
	Altitude at foot of hill				45									m
14	Orography location factor s				0.966									
15	Orography factor c_o				1.11									
16	$c_{alt(o)}$ for foot of hill				1.04									
17	Orographic $q_{p(o)} = q_p \times [(c_{alt(o)}/c_{alt}) \times (c_o + 0.6)/1.6]^2$				465									Pa
	Breadth of building b	29			20			29			20			m
	$b + h$	56			47			56			47			m
18	Size factor c_s	0.84	0.81	0.81	0.82	0.82	0.82	0.81	0.84	0.84	0.85	0.85	0.85	
	Damping δ_s	Assume 0.08												
	h/b	0.93			1.35			0.93			1.35			
19	Dynamic factor c_d	1.02			1.03			1.02			1.03			
	q_p (or $q_{p(o)}$) $c_s c_d$	584	428	379	393	394	405	465	628	752	926	911	751	Pa
20	Ditto, by quadrant	0.584			0.405			0.752			0.926			kPa
	Depth of building d	20			29			20			29			m
	h/d	1.35			0.93			1.35			0.93			
21	Force coefficient c_f	0.98			0.92			0.98			0.92			
	Shadow area A_{sh} (= bh for cuboid)	783			540			783			540			m^2
22	Significant friction?	×			×			×			×			
23	If so, $F_{fr} = q_p$ (or $q_{p(o)}$) $c_{fr} A_{fr}$	-			-			-			-			kN
24	Overall wind force $= q_p$ (or $q_{p(o)}$) $c_s c_d\ c_f\ A_{sh} + F_{fr}$ (if any)	448			201			577			460			kN
25	Higher of Q1/Q3	577												kN
	Higher of Q2/Q4	460												kN

Figure 9.3 Aerial photo of the area prior to construction

RGB Aerial Photography © GeoPerspectives

Sectors S2 to 7 inclusive face the city centre with relatively uninterrupted coverage by buildings whose average height is estimated to exceed 12 m. For these sectors, displacement height h_{dis} is taken as $0.8h_{ave} = 10$ m. Check: this does not exceed $0.6h = 16.2$ m.

Note that this assessment is based on conditions at the time the Bioincubator was designed. No account is taken of subsequent developments, on both sides of the road to the west of the building, which can be observed on more recent satellite imagery.

Stage 6

Placing the SCI wind protractor on a 1:1 000 000 map of northern England, as in Figure 5.6, it can be seen that Sheffield is over 100 km from the sea in all but two sectors. S4 includes the Humber estuary and S11 includes the Mersey at Runcorn.

Although the Humber is a wide estuary as far inland as Goole, from a Sheffield perspective it is reasonable to judge (with the authority of BRE Digest 436) that the S4 shoreline is 90 km distant at Immingham.

It might equally be argued that the wind has travelled as far over the Wirral as over the Mersey, but if a cautious view is taken the S11 shoreline is 85 km away at Runcorn.

Stage 7

Exposure factor c_e can be read from Figure NA.7 (Figure 5.9 of this Design Guide). For all sectors except S4 (90 km) and S11 (85 km), the right hand edge of the graph (100+ km) is used.

However ordinate $(z - h_{dis})$ will vary. This overall wind action calculation is for $z = h = 27$ m.

In S1, 8, 9, 10, 11 and 12, with zero displacement, $(z - h_{dis}) = 27$ m. In the remaining sectors, with 10 m displacement, $(z - h_{dis}) = 17$ m.

c_e varies between 2.67 and 2.99.

In practice, instead of consulting the graphs, it is convenient to use freely downloadable software: www.rwdi.com/encalculator_program

Note that the input 'effective height' means $(z - h_{dis})$. The zone for size factor purposes (Stage 10) is given in brackets. Beware that symbol c_e is misapplied to the product of c_e and $c_{e,T}$, though the presentation makes this fairly obvious. See Figure 9.4 for an example.

The c_r and I_v outputs are not relevant to the simpler (exposure factor) procedure of this example; they are for the more elaborate (roughness factor) treatment outlined in Appendix A.

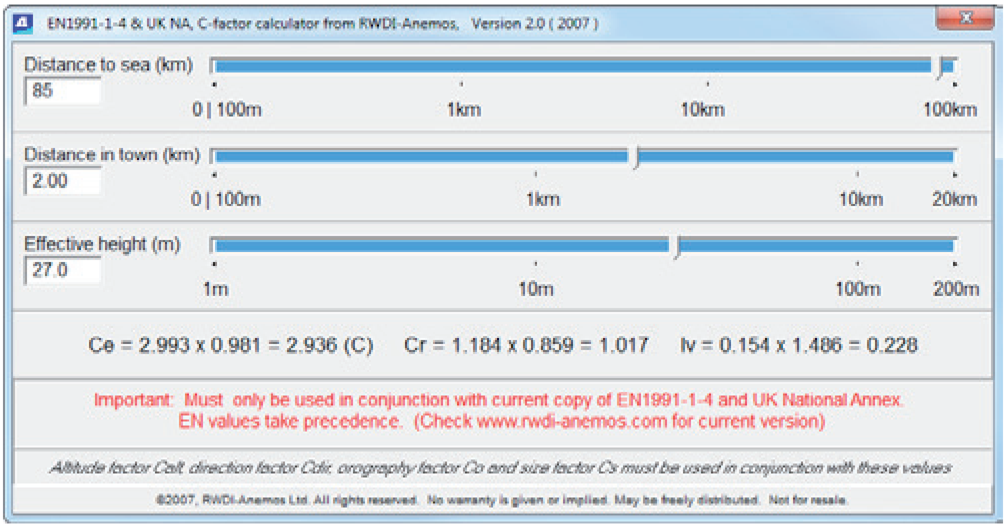


Figure 9.4 Illustration of ENcalculator program output

Stage 8

Placing the SCI wind protractor on the 1:50 000 map of Sheffield allows the distance to the nearest edge of town within each sector to be measured. For emphasis, the edge of town has been outlined in Figure 9.5. Embedded open spaces greater than 1 km in radial extent have also been outlined. It seems reasonable to overlook smaller embedded open spaces.

Sheffield is entwined with its surrounding landscape and rich in embedded open space, so it provides a challenging example. Where open space is penetrating, it is always safe, but not always reasonable, to measure to its closest point. BRE Digest 436 offers some guidelines.

Minimum distances to edge of town, some of which probably err on the safe side, have been estimated for each sector. They vary between 2 km and 5 km.

Stage 9

Figure 9.5 (Opposite) Edge of town outlined on 1:50 000 map of Sheffield (at 60%)

The town terrain correction factor $c_{e,T}$ is read from Figure NA.8 (Figure 5.11 of this Design Guide). Its value varies between 0.88 and 0.98.

Stage 10

The zone for size factor purposes, obtained from Figures NA.7/8 (Figures 5.9 and 5.11 of this Design Guide), is C for all sectors.


ROTHERHAM
RAWMARSH
SHEFFIELD
S1
S2
S3
S4
S5
S6
S7
S8
S9
S10
S11
S12

Stage 11

The peak 'non-orographic' velocity pressure is:

$$q_p \quad = 0.613(v_{map}\, c_{alt}\, c_{dir})^2 \times c_e\, c_{e,T}$$

which ranges between 455 Pa (S4) and 1058 Pa (S10).

Stage 12

The slope between the site and the Don valley exceeds 0.05 (10 contours to the kilometre on the Ordnance Survey 1:50 000 map) so the situation appears potentially 'orographic' over a number of sectors. However if a wider view is taken, the site is almost completely embraced by high ground. In Figure 9.6, the 100 m contour (the closest to site altitude) has been outlined. S4, facing directly down the valley, is clearly at risk from orographic effect. From other directions, with the partial exception of S5, equally high or higher ground protects the site. The wind will merely be regaining velocity lost on descent and the altitude factor will suffice. S5 also sees high ground on the horizon, but as this is around 10 km away (in the northernmost part of the sector) it seems prudent not to rely on it for protection.

Within the unsheltered northernmost part of S5, the radial distance to the valley floor is remeasured, more obliquely than in S4, and estimated at 1.4 km. This reduces the average slope to $\phi \approx (105 - 40)/1400 = 0.046$, which is less than 0.052. So sector S5 can be deemed 'non-orographic' by virtue of the '3° rule' of EN 1991-1-4, 4.3.3(2).

Calculations to examine the effect of orography (in Stages 13 to 17) can now be confined to S4.

Stage 13

Having identified S4 as a potentially 'orographic' sector, it is necessary to postulate an equivalent idealized landform profile, to the pattern of EN 1991-1-4 Figure A.2's escarpment or Figure A.3's ridge. Although there are other directions for which the site would be classed as a ridge, it is an escarpment from the perspective of S4. In this example, the distinction is not important because the building will be assumed to be on the crest (i.e. $X = 0$). The valley floor (altitude 45 m) provides a reasonably distinct base level at a distance of 1.1 km approx.

On this basis $\phi = (105 - 45)/1100 = 0.055$ and $L_u = L_e = 1100$ m.

Figure 9.6 (Opposite) Surrounding ground above 100 m outlined on the map

Reproduced by permission of Ordnance Survey on behalf of HMSO.

Stage 14

$$z/L_e \quad = 27/1100$$

$= 0.025$ which is below the graph of EN 1991-1-4 Figure A.2.


ROTHERHAM
RAWMARSH
SHEFFIELD
S1
S2
S3
S4
S6
S7
S8
S9
S10
S11
S12
Ecclesfield
Aughton
Wharncliffe Side
Burbage Moor
Dungworth

The expression in Section 5 (Stage 14) will therefore be evaluated:

$$s = A$$

$$= 0.1552(0.025)^4 - 0.8575(0.025)^3 + 1.8133(0.025)^2 - 1.9115(0.025) + 1.0124$$

$$= 0.966$$

Stage 15

From EN 1991-1-4 Expression (A.3), for $\phi < 0.3$,

$$c_o = 1 + 2s\phi = 1 + 2 \times 0.966 \times 0.055 = 1.11$$

This exceeds 1.05, confirming that the sector is indeed orographic.

Stage 16

Altitude factor must be recalculated for the assumed base level of the orographic feature, at the foot of the hill.

For a 27 m high building with an orographic base altitude of 45 m,

'Orographic' altitude factor

$$c_{alt(o)} = 1 + 0.001A[10/(0.6h)]^{0.2}$$

$$= 1 + 0.001 \times 45\ [10/(0.6 \times 27)]^{0.2}$$

$$= 1.04$$

Stage 17

'Orographic' velocity pressure

$$q_{p(o)} = q_p\ [(c_{alt(o)}\ /c_{alt})(c_o + 0.6)/1.6]^2$$

$$= 455\ [(1.04/1.1)(1.11 + 0.6)/1.6]^2$$

$$= 455 \times 1.021 = 465\ \text{Pa}$$

$$> 455$$

Orography has increased the wind pressure in sector S4 but only by 2%. Even with orography, S4 is one of the least onerous sectors.

Stage 18

Size factors will be based on face dimensions.

For Quadrants 1 and 3 (S1 to 3, S7 to 9) $b = 29$ m and $(b + \mathrm{h}) = 56$ m

For Quadrants 2 and 4 (S4 to 6, S10 to 12) $b = 20$ m and $(b + \mathrm{h}) = 47$ m

In Stage 10 it was established that size factor Zone C applies in all sectors. However displacement can and does vary between sectors.

From Table 5.1 of this Design Guide (or Table NA.3), size factor c_s is found to vary between 0.81 and 0.85.

Stage 19

Dynamic factor c_d will be based on an assumed logarithmic decrement of structural damping $\delta_s = 0.08$, a typical value for composite ('mixed structures concrete + steel') buildings according to Table F.2 of EN 1991-1-4 informative Annex F. Different dynamic factors will apply for the N-S direction (Q1/Q3) for which $b = 29$ m and the E-W direction (Q2/Q4) for which $b = 20$ m.

From Table 5.2 of this Design Guide, $c_d = 1.02$ (broadside on) and 1.03 (narrow side to the wind).

Stage 20

At this stage the sectors are consolidated into quadrants. For each quadrant the highest value of $q_p c_s c_d$ (or $q_{p(o)} c_s c_d$) in any of its three constituent sectors is retained. It turns out that orography has not influenced the result.

Stage 21

The wind force (excluding friction) is $q_p c_s c_d \times c_f \times A_{sh}$.

Different force coefficients c_f will apply in the N-S direction (Q1/Q3) for which $h/d = 1.35$ and the E-W direction (Q2/Q4) for which $h/d = 0.93$. In both directions $h/d < 5$ so Table 5.3 of this Design Guide is valid.

$c_f = 0.98$ and 0.92 respectively. For this cuboid building $A_{sh} = bh$, the relevant face area.

Stage 22

The Bioincubator's proportions are such that an experienced designer might exclude friction by inspection. For this cuboid building, friction may be neglected if swept area is less than eight times shadow area.

Applying this with wind narrow side on, swept area:

$$A_{sw} \quad = d(b + 2h) = 29(20 + 2 \times 27) = 2146 \text{ m}^2$$

$$8A_{sh} \quad = 8bh = 8 \times 20 \times 27 = 4320 > 2146$$

Stage 23

The calculation of friction is not required in this example.

Stage 24

In principle the force from Stage 21 is now increased by frictional force F_{fr} from Stage 23. In this example there is no friction to add because it is deemed insignificant.

The largest quadrant force is 577 kN in Q3, acting in a northerly direction. Q4 generated more intense pressure but narrow side on, resulting in a force of 460 kN acting eastwards. In both cases the forces in the opposite direction are appreciably smaller (indeed the westward force from easterly wind in Q2 is less than half of that vice versa in Q4).

Stage 25

With some bracing configurations the designer may be able to take advantage of different wind forces in opposite directions, but if not the results may simply be presented as **±577 kN N-S** and **±460 kN E-W**. These are characteristic values and will need to be factored appropriately for the design situations.

9.2 Some comparisons

For comparison, Figure 9.7 presents the same calculation for four quadrants instead of twelve sectors, with a 2% penalty in the N-S direction and less than 1% penalty in the E-W direction.

Figure 9.8 summarizes the non-directional approach, with orography as for sector S4, zero displacement, shoreline at 85 km and edge of town at 2 km producing results respectively 23% and 2% higher than the original calculation.

Figure 9.7 (Opposite) SCI Wind calculation sheet for Sheffield Bioincubator – in quadrants

Figure 9.8 (Right) Summary non-directional calculation for Sheffield Bioincubator

$$q_{p(o)} = 0.613(\underbrace{22.1}_{v_{map}} \times \underbrace{1.04}_{c_{alt(o)}})^2 \times \underbrace{2.99}_{c_e} \times \underbrace{0.98}_{c_{e,T}} \times \underbrace{1.14}_{[(c_0 + 0.6)/1.6]^2} = 1081 \text{ Pa}, 1.08 \text{ kPa}$$

$$F = 1.08 \times 0.84 \times 1.02 \times 0.98 \times 783 = 710 \text{ kN N-S}$$

$$= \underbrace{1.08}_{q_{p(o)}} \times \underbrace{0.85}_{c_s} \times \underbrace{1.03}_{c_d} \times \underbrace{0.92}_{c_f} \times \underbrace{540}_{A_{sh}} = 470 \text{ kN E-W}$$

Figures in orange are ‘orographic’ values

SCI Wind Calculation Sheet (for quadrants)

	SHEFFIELD BIOINCUBATOR (SK345873; 53°22'54"N / 1°29'W)					
1	Map wind speed v_{map}	22.1				m/s
	Height of building h	27				m
	Site altitude A	105				m
2	Altitude factor c_{alt}	1.1				
	Quadrant number	Quadrant 1	Quadrant 2	Quadrant 3	Quadrant 4	
3	Sector orientation	315	045	135	225	315 °
4	Directional factor c_{dir}	0.82	0.74	0.93	1	
5	Displacement height (if any) h_{dis}	0	10	0	0	m
	$z - h_{dis}$ $(= h - h_{dis})$	27	17	27	27	m
6	Distance to shoreline	100	90	100	85	km
7	Exposure factor c_e	2.98	2.68	2.98	2.99	
8	Distance into town	4	2	3	2	km
9	Correction factor $c_{e,T}$	0.94	0.93	0.96	0.98	
10	Zone for size factor	C	C	C	C	
11	$q_p = 0.613(v_{map} \times c_{alt} \times c_{dir})^2 \times c_e c_{e,T}$	682	494	896	1062	Pa
12	Potentially significant orography?	×	✓	×	×	
13	Upwind slope of hill Φ		0.055			
	Altitude at foot of hill		45			m
14	Orography location factor s					
15	Orography factor c_o		1.11			
16	$c_{alt(o)}$ for foot of hill		1.04			
17	Orographic $q_{p(o)} = q_p \times [(c_{alt(o)}/c_{alt}) \times (c_o + 0.6)/1.6]^2$		504			Pa
	Breadth of building b	29	20	29	20	m
	$b + h$	56	47	56	47	m
18	Size factor c_s	0.84	0.82	0.84	0.85	
	Damping δ_s	0.08				
	h/b	0.93	1.35	0.93	1.35	
19	Dynamic factor c_d	1.02	1.03	1.02	1.03	
20	q_p(or $q_{p(o)}$) $\times c_s \times c_d$	584	426	768	930	Pa
		0.58	0.43	0.77	0.93	kPa
	Depth of building d	20	29	20	29	m
	h/d	1.35	0.93	1.35	0.93	
21	Force coefficient c_f	0.98	0.92	0.98	0.92	
	Shadow area A_{sh} (= bh for cuboid)	783	540	783	540	m^2
22	Significant friction?	×	×	×	×	
23	If so, $F_{fr} = q_p$ (or $q_{p(o)}$) $c_{fr} A_{fr}$	-	-	-	-	kN
24	Overall wind force = q_p (or $q_{p(o)}$) $c_s c_d\, c_f\, A_{sh} + F_{fr}$ (if any)	448	212	589	462	kN
25	Higher of Q1/Q3	589				kN
	Higher of Q2/Q4	462				kN

In this case, the advantage of a directional approach is clear, though evaluation for four quadrants happens to be almost as productive as for twelve sectors. It would, however, be unwise to generalize from one example.

9.3 Wind on an element (the external column)

The 21 m high, 406 mm diameter external column (seen in Figure 9.1) is an example of an individual 'element' for which a separate wind calculation might be undertaken. However, lateral wind force on this column can safely be evaluated using the same peak dynamic pressure as calculated in Stage 11 (or 17) for the building as a whole. Sectors from which the column is sheltered by the bulk of the building (S1 and S12) can be disregarded. From Figure 9.2, the largest value is $q_\mathrm{p} = 1058$ Pa in S10.

Size factor is reassessed as 0.89, for $(b + h) \approx 21$ m. It would be inappropriate to apply the dynamic factor from Stage 19, but this is not to say that a slender isolated column is immune from dynamic effect. Indeed, as an element which could be vulnerable to vortex-induced vibration (see Section 4.2), it is a candidate for specialist advice.

With no end effect, a force coefficient for the circular section can be obtained directly from EN 1991-1-4 Figure 7.28. For practical purposes, Reynolds Number dependence and sensitivity to surface smoothness can be circumvented by taking $c_{\mathrm{f},0} = 1.2$.

Wind force per unit length (ignoring the 'pencil' ends, and any dynamic magnification) may therefore be evaluated as:

$$q_\mathrm{p}\, c_\mathrm{s}\, c_{\mathrm{f},0} \times \text{diameter of CHS column}$$

$$= 1058 \times 0.89 \times 1.2 \times 0.406$$

$$= 459 \text{ N/m, } \mathbf{0.46\ kN/m}$$

This is a characteristic (unfactored) value.

Alternatively, a slightly lower dynamic pressure could be obtained in return for a repeat wind calculation for $z = 21$ m (the height of the top of the element), with $z_\mathrm{s} = 12.6$ m (60% of the height of the element) in the altitude factor formula. (Note that for a horizontal element z_s would be taken at mid-height, as shown in EN 1991-1-4 Figure 6.1.)


Buses on diversion
11, 23, N11
Improving the image of construction
TC3

CLADDING DESIGN EXAMPLE

This example is a continuation from Section 9, to derive pressures for cladding specification purposes. It is assumed that the same facade design will be maintained for all faces and all levels of the building, rooftop plant room excepted. The object of this exercise is therefore to identify the numerically highest pressures acting outwards and inwards. These pressures will be based on q_{p} (or $q_{\mathrm{p(o)}}$) as previously calculated for the top of the building. This is convenient but it is also what NA.2.26 requires for the rear and side faces subject to negative pressure. It would be permissible for the positive pressure on the windward face to be recalculated for a slightly lesser height z (to top of topmost panel) and a slightly reduced altitude factor (based on z_{s} = mid-height of topmost panel, as opposed to $0.6h$). However it would be complicated, perhaps needlessly so, to evaluate a slightly different 'inwards-acting' q_{p} for cladding design. It will be safe, and less error-prone, to retain the value from Stage 11 (or Stage 17, in a sector where orography had generated a higher $q_{\mathrm{p(o)}}$).

10.1 Velocity pressure for cladding design

The highest q_{p} (or $q_{\mathrm{p(o)}}$) from Stage 11 (or 17) is 1058 Pa. If all cladding panels are to be designed for the same pressure, there is no need to differentiate between faces.

10.2 Size and dynamic factor for cladding

Neither size nor dynamic factor will be applied in this pressure calculation for cladding design purposes.

For $(b + h) \leq 5$ m, $c_{\mathrm{s}} = 1$. Therefore no size factor benefit would apply to a panel of dimensions such as 4×1 or 3×2 m. Larger panels could qualify for a size factor less than 1, but it is simple and conservative to take $c_{\mathrm{s}} = 1$ for cladding design purposes. This assumption avoids any need to consider how the panels are supported and deduct cantilever area.

The dynamic factor for a cladding panel will normally also be taken as 1 (as noted under Figure NA.9).

10.3 External pressure coefficients

For vertical and near-vertical walls of rectangular plan buildings, pressure coefficients are given in Table 6.1.

The most negative coefficient is −1.2 (in Zone A, the high local region of the side wall). The most positive is +0.8, for $h > d$.

10.4 Internal pressure coefficients

For a multi-storey building c_{pi} is commonly taken as the more onerous of +0.2 and −0.3, with the probability of a dominant opening in a severe storm considered negligible. In principle, the actual value of c_{pi} could be estimated by balancing the inward and outward flow through the various faces, as described in Section 6.2.1. The flow balance is sensitive to assumptions of (relative) permeability and to variations in build quality, so designers may judge it prudent to retain +0.2 /−0.3 in preference to a more refined calculation.

10.5 Pressure for cladding specification

In this example, it is considered reasonable to take the ‘default’ internal pressure coefficient of +0.2 in combination with an external pressure coefficient of −1.2, giving a net outwards pressure of $1.4q_p$. The net inwards pressure, similarly, is $1.1q_p$ resulting from coefficients of −0.3 internal and +0.8 external.

Cladding design should be based on a characteristic pressure of $1.4 \times 1058 = 1481$ Pa, say **1.48 kPa**, acting outwards.

If the panels are not equally resistant in the other direction, the facade designer may take advantage of a lower inwards characteristic pressure of $1.1 \times 1058 = 1164$ Pa, say **1.16 kPa**.

For strength verification of a cladding panel, wind is generally the only significant design action and a partial factor of $\gamma_Q = 1.5$ will be applied to these characteristic values to give the design value of wind pressure.

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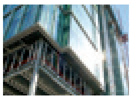
CREDITS



Cover Snowhill Building, Birmingham

vi Brock Street, London

xii Bishopsgate, London

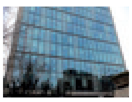
7 Fenchurch Street, London

12 Heron Tower, London

15 More 7, London

56 The Shard, London

60 Snowhill Building, Birmingham



67 St Botolph Building, London

77 Heron Tower, London

85 Canada Square, London


HSBC

APPENDIX A: THE MORE ELABORATE TREATMENT

This is the procedure represented by the lowest two boxes of the flowcharts given in Figures A.NA.1 and A.NA.2 of the NA. It is referred to in this Design Guide as the 'more elaborate treatment' and is obligatory for buildings more than 50 m high in 'orographic' situations. The procedure is placed in this appendix because readers may prefer not to engage with it until commissioned to design such a building.

The more elaborate treatment is universally applicable. In the absence of significant orography, with $c_o = 1$, it should give the same result as the simpler treatment of Section 5. All sectors, whether or not they prove to be 'orographic' can be evaluated using the more elaborate treatment.

Exposure factors play no part in the more elaborate treatment. Figures NA.7 and 8 (Figure 5.9 and Figure 5.11 of this Design Guide) are consulted but only for the purpose of zone assignment. Instead, Figures NA.3, 4, 5 and 6, and 'roughness' factors, are relevant. Roughness factors replace exposure factors but they are not directly equivalent. They apply to velocity, not velocity pressure, and the velocity they apply to is the mean velocity, not the peak. Mean velocity excludes turbulence, whose intensity is obtained from Figures NA.5 and 6.

As with the simpler (exposure factor) approach, a convenient alternative to the graphs is the freely downloadable ENcalculator program (see Figure 9.4 and reference 12).

Essentially, the additional elaboration is to keep separate account of mean velocity (which is locally amplified by orography) and turbulence (which is not). Peak velocity is a combination of the two, so is increased, but not pro rata to the mean. In the simpler treatment (restricted to buildings up to 50 m high), this is allowed for in relatively ad hoc fashion by the $[(c_o + 0.6)/1.6]^2$ factor on peak pressure (equivalent to $[(c_o + 0.6)/1.6]$ on peak velocity), diluting the impact of c_o itself. In principle, the more elaborate treatment ought to generate a more accurate result where orography is involved.

Although only compulsory for buildings higher than 50 m, the more elaborate treatment is valid for all heights. The designer of a lower building on a sea cliff might consider adopting it voluntarily, since the assumption of a compromise gust factor of 1.6 (on which the simpler treatment is based) is on the unconservative side for a maritime boundary layer.

The stages of the simpler treatment (Section 5) are followed except as detailed below.

Stage 7 is replaced by:

Roughness factor

Enter the graph of Figure NA.3 to determine the roughness factor c_r for each sector.

Turbulence intensity

Enter the graph of Figure NA.5 to determine the intensity of turbulence $I_{v,flat}$ for each sector.

Zone assignment

Note also, in Figure NA.7, whether Zone A or B applies. This will be used later in the determination of size factor. If the site is in town, this zone assignment is a provisional one which may be overridden later.

Stage 9 is replaced by:

Town terrain roughness correction factor

Enter the graph of Figure NA.4 to determine the town terrain roughness correction factor $c_{r,T}$ for each sector.

Town terrain turbulence correction factor

Enter the graph of Figure NA.6 to determine the town terrain turbulence correction factor $k_{I,T}$ for each sector.

As in Figure NA.8, the ≤ symbol at bottom left of both of these graphs is incorrect; sites less than 100 m into town are treated as country.

Stage 11 is replaced by:

Calculation of velocity pressure ('non-orographic')

Peak velocity pressure is calculated sector by sector as:

$$q_p = 0.613\,[v_{map}\,c_{alt}\,c_{dir}\,c_r\,c_{r,T}\,(1 + 3I_{v,flat}\,k_{I,T})]^2$$

in which $c_{r,T}$ and $k_{I,T}$ are set equal to 1 if the site is not in town.

This is without the influence of orography. Even in an 'orographic' situation, the 'non-orographic' calculation is required.

For sectors identified as 'orographic', Stage 17 is replaced by:

Recalculation of velocity pressure ('orographic')

Peak velocity pressure is recalculated as:

$$q_{p(o)} = 0.613\,[v_{map}\,c_{alt(o)}\,c_{dir}\,c_r\,c_{r,T}\,(c_o + 3I_{v,flat}\,k_{I,T})]^2$$

in which $c_{r,T}$ and $k_{I,T}$ are set equal to 1 if the site is not in town.

Note that $c_{alt(o)}$ represents the reduced altitude factor calculated for the foot of the hill in Stage 16. c_o is the orography factor calculated in Stage 15.

Compare the 'orographic' peak velocity pressure $q_{p(o)}$ with the original 'non-orographic' q_p. Use whichever is larger. The 'non-orographic' calculation can give a more onerous result in some cases.

Proceed from Stage 18

APPENDIX B: DESIGN ACTIONS FOR NON-STANDARD DURATIONS

Although not required for the structural design of normal buildings in their final condition, factors c_{prob} and c_{season} may be relevant when considering temporary buildings or transient conditions during execution. Both these factors apply to the wind velocity alongside c_{alt} and c_{dir}. If both apply, the Stage 11 expression expands to:

$$q_p = 0.613(v_{map} \times c_{alt} \times c_{dir} \times c_{prob} \times c_{season})^2 \times c_e c_{e,T}$$

B.1 Probability factor

The probability factor c_{prob} allows for exposure periods different from 50 years.

$$c_{prob} = 0.75\sqrt{1 - 0.2\mathrm{Ln}[-\mathrm{Ln}(1-p)]}$$

in which p is the annual probability of exceedance, with a value of 0.02 for the customary 50 year 'indicative' working life.

Buildings of non-standard design life

The UK NA to EN 1990, in its Table NA2.1, suggests indicative working lives which range between 10 years for temporary structures and 120 years for 'monumental' buildings. The formula is equally valid for lifetimes over 50 years, for which it will yield a probability factor greater than 1.

As an example, if the client for an agricultural building specifies a 25 year design working life, p can be doubled to 0.04 and the formula gives $c_{prob} = 0.96$. Conversely, a brief for 120 years would lead to $p = 1/120 = 0.0083$ and $c_{prob} = 1.05$.

Transient design situations

The probability factor is also applicable in transient design situations such as the verification of temporary bracing for a retained facade. Incomplete buildings may require verification at various stages of construction or demolition. For example an unclad frame can attract a wind force which exceeds that of the clad structure; at the same time, part of the self weight that counters overturning may be lacking. BRE Digest SD5[20] provides information on wind action on unclad structures.

For transient design situations in course of construction, it is prudent to allow for a working life of 5 years even if the situation is only intended to prevail for 3 months or less. This leads to $p = 0.2$ and $c_{prob} = 0.855$, say 0.85, as minimum. This is in line with EN 1991-1-6[21] Table 3.1, which would also, for a duration between 3 months and 1 year, recommend a minimum of 0.9 (as for a temporary building with a 10 year indicative working life). These informative recommendations are endorsed by the relevant UK NA.

BS EN 1991-1-6 Table 3.1 does allow c_{prob} to be taken as low as 0.78, but only for exposure of 3 days or less. For transient situations of such short duration the alternative of waiting for a 'weather window' may be available (but see Section B.3). The BCSA Guide to Steel Erection in Windy Conditions[22] contains relevant advice.

A cautionary example of a transient design situation that became quasi-persistent is the 'temporary' steelwork bracing the walls of the former Battersea Power Station, in service for over 25 years (Figure B.1).

Figure B.1 Battersea Power Station in 2006

Photograph by Ian Mansfield, courtesy of Wikipedia (www.wikipedia.org). Released under the GNU Free Documentation License.

B.2 Season factor

For less than year-round exposure c_{season} is available. Table NA.2 gives values of this factor (which is always a reduction factor) for a selection of periods and times of year. For obvious reasons, c_{season} should be used with caution, subject to thorough client understanding and consent.

An example of a summer-only structure is Holland Park Theatre (Figure B.2). From Table NA.2, a factor of $c_{season} = 0.73$ may be applied in the design of a structure which is erected each May and dismantled each August, almost halving design wind actions in comparison with a structure which remains in place all year.

Figure B.2
Holland Park Theatre

Photograph by Fritz Curzon. Courtesy of the Royal Borough of Kensington and Chelsea

A frame which remains unclad for a period of a few non-winter months is an example of a transient design situation for which it would, in principle, be acceptable to apply both c_{prob} and c_{season}, but the need for caution and consent is re-emphasized. If a pessimistic view of the construction programme reveals any possibility of overrun into December/January, only c_{prob} can be applied.

B.3 Minimum wind

Mention should also be made of the recommendation, not in EN 1991-1-4 but in EN 1991-1-6, that a 20 m/s 'basic value' of wind speed be assumed as a minimum in execution situations of up to 3 months duration. The effect, in the expanded Stage 11 expression:

$$q_{\text{p}} \quad = 0.613(v_{\text{map}} \times c_{\text{alt}} \times c_{\text{dir}} \times c_{\text{prob}} \times c_{\text{season}})^2 \times c_{\text{e}} c_{\text{e,T}}$$

would be to replace $(v_{\text{map}} \times c_{\text{alt}} \times c_{\text{dir}} \times c_{\text{prob}} \times c_{\text{season}})$ by 20 m/s, if that is greater. However, the recommendation does not have normative status and the velocity is open to national determination. The UK NA to EN 1991-1-6[23] declares that 'the recommended value should be defined for the individual project', which may be interpreted as licence to ignore. Alternatively, the statement in the UK NA may be interpreted as an invitation to give serious consideration to the possibility of what might be described as a 'bolt from the blue'. In statistical terms such events are outliers, and their velocity is difficult to estimate. A figure such as 20 m/s is somewhat arbitrary, but serves (together with the partial factor) to maintain a level of defence against the unexpected.

If official guidance seems less definite than might be desired, this may be a reflection of the variation in severity of transient situations in constructional engineering practice. Many experienced designers and constructors would advocate a risk analysis in which the consequences of failure are given due weight. In sensitive situations it may be judged inappropriate to exploit c_{prob} and/or c_{season} to the full extent that is acceptable where the risk is minor.

APPENDIX C: CALCULATION AIDS

The SCI Wind Protractor (as in Figure 5.2) is presented here at full scale. This can be photocopied onto transparent film for use with maps and air views at various stages of the procedure.

The manual calculation sheet is a blank version of the one which illustrates the design example. It can be used to facilitate and present a directional calculation in stages according to the procedure of Section 5. It is for twelve 30° sectors whose orientation is chosen to suit the building, as recommended at Stage 3, such that each face-centred quadrant comprises three sectors. The pale blue and gold background shading is to distinguish the principal directions of a rectangular plan shape.

For a calculation which is based on four face-centred quadrants from the start, the same sheet can be used with sector subdivisions ignored.

SCI Wind Calculation Sheet

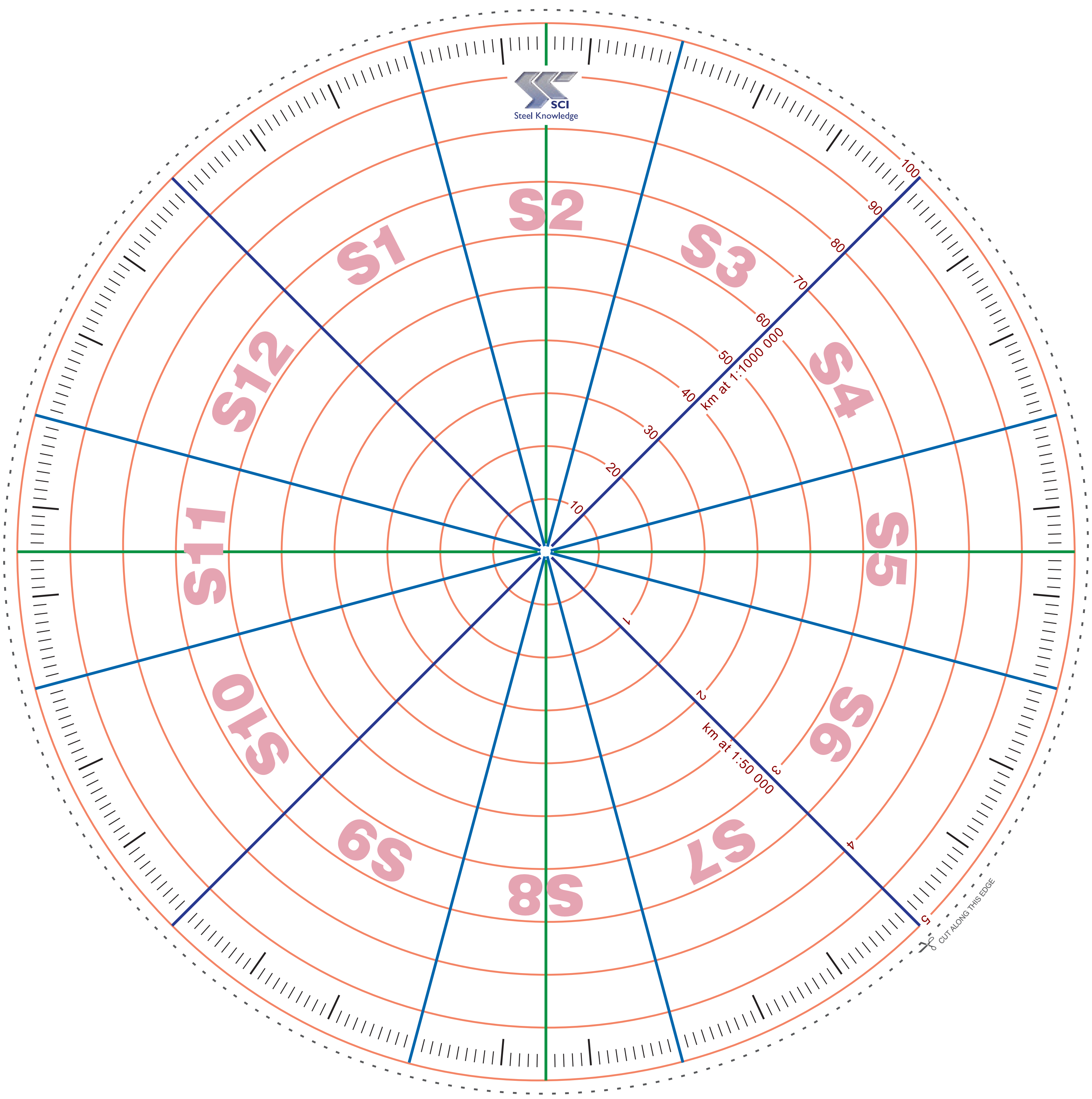
	LOCATION:													
1	Map wind speed v_{map}													m/s
	Height of building h													m
	Site altitude A													m
2	Altitude factor c_{alt}													
	Quadrant number	Quadrant 1			Quadrant 2			Quadrant 3			Quadrant 4			
	Sector number	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	
3	Sector orientation													°
4	Directional factor c_{dir}													
5	Displacement height (if any) h_{dis}													m
	$z - h_{dis}$ $(= h - h_{dis})$													m
6	Distance to shoreline													km
7	Exposure factor c_e													
8	Distance into town													km
9	Correction factor $c_{e,T}$													
10	Zone for size factor													
11	$q_p = 0.613(v_{map} \times c_{alt} \times c_{dir})^2 \times c_e c_{e,T}$													Pa
12	Potentially significant orography?													
13	Upwind slope of hill Φ													
	Altitude at foot of hill													m
14	Orography location factor s													
15	Orography factor c_o													
16	$c_{alt(o)}$ for foot of hill													
17	Orographic $q_{p(o)} = q_p \times [(c_{alt(o)}/c_{alt}) \times (c_o + 0.6)/1.6]^2$													Pa
	Breadth of building b													m
	$b + h$													m
18	Size factor c_s													
	Damping δ_s													
	h/b													
19	Dynamic factor c_d													
	q_p (or $q_{p(o)}$) $c_s c_d$													Pa
20	Ditto, by quadrant													kPa
	Depth of building d													m
	h/d													
21	Force coefficient c_f													
	Shadow area A_{sh} (= bh for cuboid)													m²
22	Significant friction?													
23	If so, $F_{fr} = q_p$ (or $q_{p(o)}$) $c_{fr} A_{fr}$													kN
24	Overall wind force = q_p (or $q_{p(o)}$) $c_s c_d\ c_f A_{sh} + F_{fr}$ (if any)													kN
25	Higher of Q1/Q3													kN
	Higher of Q2/Q4													kN

SCI Wind Protractor

The Wind Protractor may be copied full size onto transparent film for use on maps at scales of 1:1000 000 and 1:50 000.
If the green lines are aligned with the axes of the building, sectors will straightforwardly consolidate into quadrants at Stage 20.

If copied, the dimensions of the copy should be verified using the scale below:

0 1 2 3 4 5 cm



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WIND ACTIONS TO BS EN 1991-1-4

For most buildings in the UK, wind action is an important influence on structural design. BS EN 1991-1-4:2005+A1:2010 (the UK implementation of Eurocode 1 Part 1-4) provides a design standard which is up to date, authoritative and, in many respects, a significant evolutionary advance. This Design Guide sets out a straightforward procedure by which wind actions (both overall forces and local pressures) can be evaluated in accordance with the new standard. A comprehensive worked example demonstrates the procedure for a typical steel framed building.

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