BRE Digest
Concise reviews of building technology
Digest 346
July 1989

#3897

The assessment of wind loads

Part 1: Background and method

This is the principal Digest in a series which is compatible with the forthcoming British Standard BS 6399:Part 2. As this new Standard incorporates several changes from the previous CP3 Chapter V:Part 2: 1972, it is considered appropriate to introduce this series of Digests by providing some background and guidance to the new provisions.

This Digest considers the assessment of wind loads on domestic, commercial and industrial buildings and their associated ancillary constructions. It describes:

- **the procedures used in assessing wind loads;**
- **the principal changes in practice between the old BS and its replacement;**
- **the response to wind effects of different structures;**
- **the wind climate and the derivation of wind speeds to be used in design**
- **load assessment and pressure coefficients.**

This Digest supersedes Digest 119 which is now withdrawn.
The other parts to this Digest series are:

Part 2 Classification of structures

Part 3 Wind climate in the UK

Part 4 Terrain and building factors and gust peak factors

Part 5 Assessment of wind speed over topography

Part 6 Loading coefficients for typical buildings

Part 7 Wind speeds for serviceability and fatigue assessments

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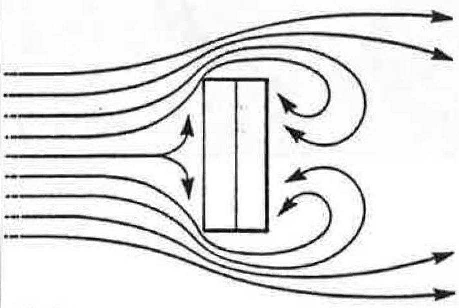

Fig 1a

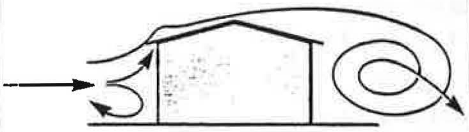

Fig 1b

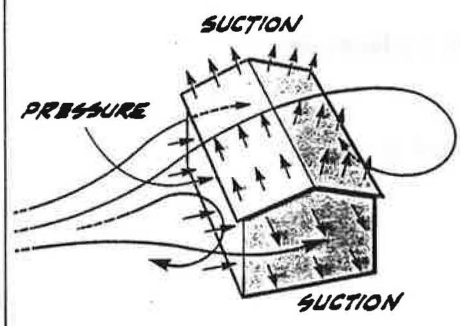

Fig 1c

GENERATION OF PRESSURES AND SUCTIONS

When the wind blows more or less square-on to a building, it is slowed down against the front face with a consequent build-up of pressure against that face. At the same time it is deflected and accelerated around the end walls and over the roof with a consequent reduction of pressure (ie suction) exerted on these areas. These effects are shown in Figure 1. The greater the speed of the wind, the greater will be the suction.

The sides of a building can experience severe suction, and it is greatest near the windward edge. Access openings through and under large slab-like blocks are usually subjected to high wind speeds because of the pressure difference between the front and rear faces of the building. The facings of such openings are particularly prone to high suction which may damage the glazing and cladding.

Channelling of the wind between two buildings causes some additional suction effects on the sides facing the gap between them.

The wake behind the building is a low pressure region which exerts a suction on the rear face. This is of lower intensity than that on the sides of the building.

In the wake of a building the flow has reduced momentum providing substantial shelter from the mean flow to other buildings downwind, although the peak pressures and suctions are not reduced to the same extent. This shelter is not exploited in BS 6399:Part 2 or in other current Codes of practice.

Effect of roof pitch

On the windward slope of a roof, the pressure is dependent on the pitch. When the roof angle is below about 30°, the flow separates and the windward slope can be subjected to severe suction. Roofs steeper than about 35° generally present a sufficient obstruction to the wind for the flow to remain attached and a positive pressure to be developed on their windward slopes. Even with such roofs there is a zone near the ridge where suction is developed and insecure roof coverings may be dislodged. Leeward slopes are always subject to suction. Gabled roofs of all pitches are affected by suction along their windward edges when the wind blows along the direction of the ridge — see Figure 2. This does not occur with hipped roofs.

The suction over a roof, particularly a low-pitched one, is often the most severe wind load experienced by any part of a building. Under strong winds the uplift on the roof may be far in excess of its self weight, requiring firm positive anchorage to prevent the roof from being lifted and torn from the building.

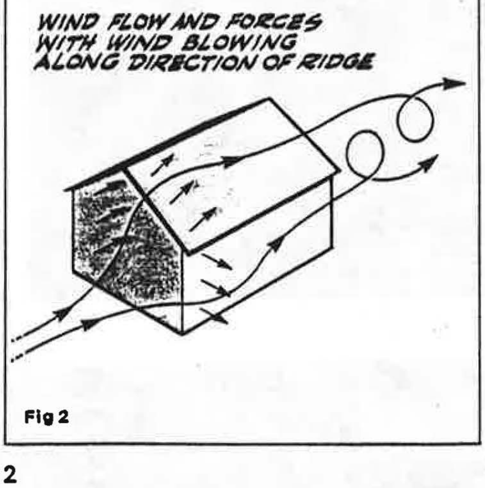

Fig 2

Variation of pressure over a surface

The distribution of pressure or suction over a wall or roof surface is generally far from uniform. Pressure tends to be greatest near the centre of a windward wall and falls off towards the upwind edges. The most severe suction is generated at the corners and along the edges of walls and roofs; careful attention must be paid to the fixings at these locations.

Any projecting feature, such as a chimney stack, dormer window or tank room, will generate eddies in the air flow causing local loads on the feature as well as modifying the loads on the roof in their vicinity. The roof cladding around projections needs special attention. Roof overhangs are subject to an upward pressure on the underside which must be taken into account in assessing the total roof uplift. These effects are described in more detail in Part 6.

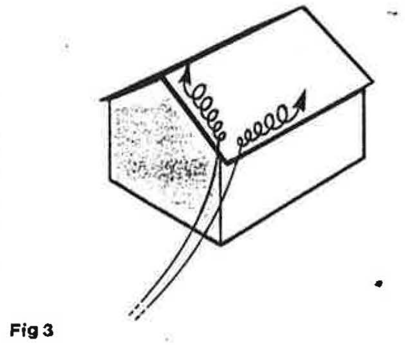

Fig 3

Vortex action on roofs

When the wind blows obliquely on to a building it is deflected round and over the building. The pressures on the walls are generally less severe than where it blows square-on, but strong vortices are generated as the wind rolls up and over the edges of the roof — see Figure 3. These give rise to very high suctions on the edges of the roof which must be resisted by especially firm fixing of the roof structure and covering. Since at most sites the wind can blow from any direction, *all edges and corners need special attention* — see Figure 4. Most wind damage to roofs is caused by this effect.

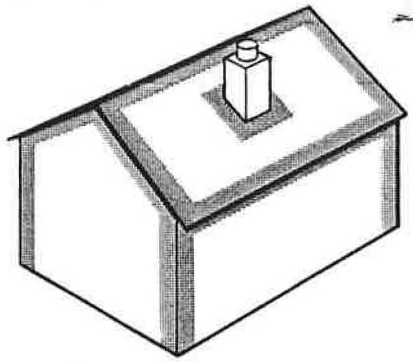

Fig 4

THE RESPONSE OF BUILDINGS TO THE WIND

The response of buildings to wind effects is strongly dependent on the characteristics of the building itself. The principal features are the natural frequency of the first few modes of vibration and the size of the building. A small structure will be completely loaded by quite small gusts but as the size increases the smaller gusts will not act simultaneously and will tend to cancel each other. Only the longer period gusts, of lower overall intensity, are significant.

A stiff building will have a high natural frequency of vibration and will tend to follow any fluctuations of load without magnification. The only design parameter to be considered is the maximum load likely to be experienced in the building's intended lifetime. Such a building is described as *static* for wind loading design purposes.

Conversely, a flexible building will have a low natural frequency: only those components of load at frequencies below the natural frequency of the structure will not be modified. Load fluctuations above the natural frequency will be attenuated in the response; the response at fluctuations near the natural frequency will be amplified, such that it may be greater than the static component. Such a structure is described as *dynamic.*

When a structure becomes very flexible the deflection may interact with the aerodynamic loads to produce various types of instability. Such structures are described as *aeroelastic.*

The majority of buildings constructed are static and can clearly be recognised as such. Only a very few are potentially aeroelastic; they are usually specialised structures. In between, there is a wide range of structures, completely static to highly dynamic. If the dynamic magnification of the response is small, this can be handled by the application of a magnification factor to the static response such that the general procedures used for the design of 'static' structures can be used. For more dynamically sensitive structures, full dynamic response procedures are necessary.

If a structure is predicted to be aeroelastic, its design has to be modified so that the interaction of the structural response with the wind is reduced. The instabilities can then be avoided and the structure is then considered as dynamic.

Methods have been developed to enable the designer to categorise his structure simply so that it can be designed by the appropriate method. This simplified procedure is described in Part 2.

WIND CLIMATE

The nature of the wind

Within the area of a wind storm, many local influences modify the general wind flow. There is a convection causing mixing of the air masses, and a mechanical stirring caused by the friction of the air over the ground. The scale of the turbulence varies over wide limits. Some of the major eddies may be several thousand metres in extent and give rise to squalls lasting several minutes. At the other end of the scale, small (though possibly severe) eddies may be due to the passage of the wind past a building or other minor obstruction. They may last only a fraction of a second. Usually the pattern is complex with small eddies superimposed on larger ones, so that wind speeds vary greatly from place to place and from moment to moment. The result of any measurement of wind speed will depend on the duration over which the sample is taken. A long averaging time allows the inclusion of a large eddy, while a brief averaging time may cover only a small superimposed eddy, but this may have a higher speed.

Wind speeds in the United Kingdom

The United Kingdom lies in the range of latitudes where the climate is characterised by the eastward passage of large weather systems. As the UK is in the southern part of this latitude range, most depressions pass over or to the north of Scotland resulting in a marked gradient in the increasing severity of strong winds in the UK from south-east to north-west.

The greatest risk is from the direction of the prevailing winds: from the south-west. As the UK is small compared with the depressions which cause strong winds, directional characteristics show no significant variation with location after correction for the site exposure. This is also true of the seasonal variations: January is the windiest month and the least windy period is between June and August. These effects are described in detail in Part 3 where design values are given.

Wind speeds in other countries

The climate of the UK is dominated by prevailing westerly winds caused by large frontal depressions. Other storm mechanisms, such as squalls, thunderstorms or tornadoes, either produce less strong winds or have very low probabilities of occurrence and can be ignored in design. This is not the general case in other countries. Tropical regions are subject to hurricanes, cyclones or typhoons with intensities and likelihood of occurrence higher than winds from general frontal depressions. In such cases, the estimation of wind speeds is more difficult than for the UK and the mixed climate data have to be separated before analysis can be undertaken. Owing to the likely greater dispersion of these wind speeds, higher safety factors are frequently required to achieve the same level of reliability as that adopted for the UK.

There are regions, including parts of the UK, where there is a risk of tornadoes or other local intense storms for which the wind speeds cannot be predicted by the method in this Digest. If these need to be considered in design, recourse has to be made to local records which include such phenomena; usually, special local regulations will apply. In the UK the risk of tornadoes is considered only for high security structures, such as nuclear power plants.

DESIGN WIND SPEEDS

The wind speed to be used in design must take into account several parameters.

These are:

- the location of the site in the UK
- the altitude of the site
- the direction of the wind
- the seasonal exposure of the structure
- the terrain in which the building is sited
- the height of the building
- the dimensions of the building
- the topography, when significant (ie if the site is at, or near, the crest of a hill, ridge or escarpment).

The detailed procedures taking these parameters into account to derive the wind speed for design are set down in later parts of this Digest, but an outline description of each is given below.

Location *Part 3*
The majority of design applications are concerned with the performance of a building over many years, so the extreme wind speeds used for design purposes have been chosen to have an annual probability of exceedence of 0.02. Analysis of wind data has provided isopleth contours on a map of the UK of such extreme wind speeds. The location of the site is the first requirement in the design process, so that the appropriate wind speed can be read from the map.

Altitude *Part 3*
Wind speed increases with altitude and so the map speed (which is related to a uniform level of 10 m above sea level) must be modified for the altitude of the site.

Direction *Part 3*
The prevailing winds are from the south-west; for buildings which are wind-direction sensitive, appropriate allowance can be made for the reduced wind speeds from other directions.

Seasonal exposure *Part 3*
Allowance can be made for the fact that winter months are the most windy, summer months the least. This can be useful for temporary works during construction.

Terrain *Part 4*
As the wind blows from the sea over the land, and from rural to urban terrain, it is slowed down but made more turbulent. This is due to increased surface friction. Account must be taken of the distance of the site from the sea and whether the site is in country or rougher town terrain.

Height of building *Part 4*
Wind velocity increases with height, the variation depending on the terrain upwind of the site.

Dimensions of building *Part 4*
For static structures it is necessary to derive the appropriate size, and from that the intensity, of gust which will embrace the loaded area of the building. The appropriate wind load is then derived from that gust speed.

Topography *Part 5*
The map wind speed, corrected for altitude, takes account of the general level of the site above sea level. It does not allow for local topographic features such as hills, valleys, cliffs, escarpments or ridges. These can significantly alter the wind speed in their vicinity.

Near the summits of hills, or the crests of cliffs, escarpments or ridges, the wind speed will be accelerated. In valleys or near the foot of cliffs the flow may decelerated. In all cases, the variation of wind speed with height is modified from that appropriate to level terrain by a topography factor.

In terrain that is sensibly level (that is where the average slope of the ground does not exceed 0.05 within a 1 km radius of the site) the effect of topography is negligible.

LOAD ASSESSMENT FOR STATIC STRUCTURES

For most typical buildings, two aspects must be considered:

- the load on the structural frame taken as a whole;
- the loads on individual units, such as the walls and roof, their elements of cladding and fixings.

The appropriate gust speed for each aspect must be derived, differing due to the appropriate dimensions, and converted to a dynamic pressure to obtain the winds loads.

The dynamic pressure of the wind

If the wind is brought to rest against the windward face of an obstacle, all its kinetic energy is transferred to a pressure q, sometimes referred to as the *stagnation pressure* or *dynamic pressure*.

This is calculated:

$$q = kV_{REF}^2 \ \text{N/m}^2$$

where $k = 0.613$ kg/m³

V_{REF} = wind speed in m/s

Pressure on a surface

The pressure on any surface exposed to the wind varies from point to point over the surface, depending on the direction of the wind and the pattern of flow. The pressure p at any point can be expressed in terms of q by the use of a pressure coefficient C_p. Thus:

$$p = C_p q$$

A negative value of C_p indicates that p is negative (a suction rather than a positive pressure). The load on a structure or element from the pressure or suction always acts in a direction normal to the surface.

In assessing the overall loading on a structure (for example, for the design of foundations) only overall coefficients are required, but this would not be adequate generally. In the calculation of wind load on any structure or element it is essential to take account of the pressure difference between opposite faces. For clad structures it is necessary to know the internal pressure as well as the external values, and it is convenient to use distinguishing pressure coefficients C_{p_e} and C_{p_i} to differentiate between them.

Pressure coefficients for typical rectangular buildings are given in Part 6. Other building types are covered by specific Digests (eg Digest 284 *Wind loads on canopy roofs*).

Allowances for dynamic response

As already noted, the majority of structures can be treated as static but a magnification factor can be applied to the static loading to account for any small dynamic amplification. This factor is a function of the type of building, its height, frequency of vibration and damping characteristics. It also depends on the basic wind speed for the site and, to a lesser extent, on the terrain in which the building is situated. Part 2 describes the simplifying assumptions that have been incorporated in tables from which the magnification factor can be derived for the majority of normal buildings. Where such assumptions are inappropriate, or where a more accurate derivation of the factor is required, the necessary equations are provided.

The loading for static structures is $P = p\, C_R A$

where: p is the pressure on the surface

C_R is the magnification factor

A is the reference area

Load factors

The load P derived from the above procedure has been assessed by statistical analysis of the data to be the load having an annual probability of exceedance of 0.02. The combinations of wind speed, pressure coefficients and dynamic magnification factor have been chosen such that this level of probability is provided for the loading.

The loads may thus be used with appropriate partial load and materials factors for both serviceability and ultimate loading conditions. The derivation of the partial factors has been determined separately and is not considered in these Digests.

DESIGN PROCEDURE
The stages required to derive wind loads on buildings and cladding are:

- Determine whether the structure can be treated as static and hence within the scope of the procedures covered by these Digests. The criterion is described in Part 2 and is dependent on the geometric and structural parameters of the building. From this Digest the relevant dynamic magnification factor is determined. Additional parameters are required if a more accurate value to the factor is required.
- Determine the site wind speed for each wind direction required from Part 3, dependent on the location and latitude of the site, and on the seasonal exposure of the structure.
- Determine the reference wind speed for design purposes from Part 4, using the site wind speed and the appropriate gust size dependent on the terrain of the site.
- Determine whether the reference wind speed needs to be modified for the effects of topography using Part 5.
- Determine the loading on the structure from:

  the reference wind speed;

  the dynamic magnification factor obtained from Part 2;

  the pressure coefficients from the Digest appropriate to the particular building type.
- Apply the appropriate partial load factors for the ultimate or serviceability limit state.

FURTHER READING

British Standards Institution

CP3: Code of basic data for the design of buildings
Chapter V:Part 2:1972 Wind loads

BS 6399: Loading for buildings
Part2 Wind loading (*in preparation*)

Building Research Establishment

COOK, N J. The designer's guide to wind loading of building structures. Part 1: Background, damage survey, wind data and structural classification. BRE Report. London, Butterworths, 1985. (Part 2: Static structures *to be published late 1989*).

COOK, N J, The assessment of design wind speed data: manual worksheets with ready-reckoner tables. Garston, BRE, 1985.

COOK, N J; SMITH, B W and HUBAND, M V. BRE Program STRONGBLOW : user's manual. BRE microcomputer package. Garston, BRE, 1985.

Other BRE Digests

141 Wind environment around tall buildings
206 Ventilation requirements
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The assessment of wind loads

Part 2: Classification of structures

This is the second in a series of Digests which is compatible with the proposed British Standard BS 6399:Part 2. It deals with the methods developed to categorise structures according to their sensitivity to dynamic behaviour when subjected to wind loading.

These methods allow the majority of structures to be designed statically, as at present. Mildly dynamic structures can still be treated statically by using a dynamic magnification factor. The procedures have been simplified in the British Standard so that only basic structural and geometric parameters are used to assess the appropriate category of structure, and to define whether it can be designed statically or, in very rare cases, whether a full dynamic treatment is required.

BACKGROUND TO CLASSIFICATION

A number of methods of analysing structures for wind effects are available; they range from simple static loading to sophisticated statistical methods using power spectral techniques. Generally, the simple methods can be used with adequate accuracy for most everyday building structures. It is only in the case of wind sensitive structures, such as tall, slender towers and major bridges, where wind effects are the principal loading to be considered that the more advanced methods are needed. With these, the structure's inherent flexibility is likely to make them respond more significantly to wind effects. Between the extremes there are buildings which may exhibit some dynamic magnification, that is they may respond more severely than predicted from an equivalent static load. Up to now, the designer has had no way of knowing whether or not his structure will respond in this way.

The purpose of the classification procedures is to make this distinction quantitatively and to define the appropriate analytical procedure to be used.

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Technical enquiries to:
Building Research Establishment
Garston, Watford, WD2 7JR
Telex 923220 Fax 664010

FULL PROCEDURE

Static structures

Small stiff structures, including cladding panels and conventional low-rise buildings, can be assessed using static methods and are small enough for the relevant wind information to be specified as a wind speed at a single point in space. No allowance is needed for variation of wind speed over the surface of the structure nor will the structure respond to any dynamic magnification.

Larger stiff structures can also be designed statically, but account may need to be taken of the variation of wind speed over the surface of the structure, so that advantage can be taken of the reduction in wind speed averaged over the whole surface. The size of the building can be defined by a diagonal dimension for design purposes. The appropriate gust can be determined from the gust peak factor, dependent on the height of the structure and the relevant diagonal dimension. This is described in Part 4.

Dynamic structures

These structures are not stiff enough to be assessed by static methods, but remain sufficiently stiff to prevent aeroelastic instabilities, such as vortex response, galloping and flutter. Such structures are likely to respond significantly to wind effects with large deflections causing cracking of partitions etc, and motion sickness to occupants. They require a full dynamic response analysis to assess the effects of wind loading and are excluded from the scope of BS 6399:Part 2.

Classification of static and dynamic structures

To assess the response of structures, a parameter K_F was defined relating the actual displacement of the structure, in its lowest frequency mode, to the corresponding static displacement. It can then be inferred that:

- A value of $K_F = 0$ indicates the structure is small and static responding to short high-intensity gusts.
- A value of $K_F < 0$ indicates the structure is large and static responding to lower intensity gusts.
- A value of $K_F > 0$ indicates the structure responds more than from a short intensity gust and is therefore dynamic.

When K_F is between about 0.1 and 2.0, the structure will be mildly dynamic; this warrants an increase in loading above the quasi-static values, but not enough to require a full dynamic analysis. The peak deflection (and hence peak internal forces) can be obtained by applying a factor to the static deflection where the factor is the ratio of the actual to static peak deflections. This is defined as the dynamic magnification factor C_R given by:

$$C_R = \frac{1 + (S_G^2 - 1)\sqrt{1 + K_F \quad K_T}}{S_G^2} \qquad (1)$$

where S_G is the gust factor appropriate to the size of the structure and terrain (see Part 4);

K_T = 1.33 for sea terrain
1.00 for country terrain
0.75 for town terrain

By this mean 'mildly' dynamic structures can still be designed statically by applying C_R to the static load effects. Only those structures where K_F exceeds about 2.0 (implying $C_R > 1.4$) require a full dynamic analysis. Calibration studies have shown that this static approach, using the dynamic magnification factor, can be used with confidence up to $C_R \simeq 1.5$.

SIMPLIFIED PROCEDURE

The designer is interested only in whether he can use a static procedure and, if so, what value of C_R he should adopt. Consequently, a direct reading graph of C_R has been derived dependent only on the parameters:

H the building height
n_o the frequency of the lowest mode
ζ the damping ratio
$\bar{V}_B$ the basic hourly mean wind speed

The resulting expression for K_F is:

$$K_F = \left(\frac{S_S}{24 n_o^2 b}\right)^{2/3} \left(\frac{\bar{V}_B}{24}\right)\left(\frac{1}{\zeta}\right) \qquad (2)$$

where $S_S = S_{SC}$ for country terrain
$S_{SC}S_{CT}$ for town terrain

For preliminary classification purposes, n_o is assumed to be given approximately by: $60/\sqrt{bH}$ and $\bar{V}_B$ may be assumed to be 24 m/s

where b is the diagonal of the building given by

$b = \sqrt{H^2 + W^2}$

where W is the width of the building

Thus

$$K_F = \frac{K_H}{K_B} \qquad (3)$$

where

$$K_H = (S_S H)^{2/3} \qquad (4)$$

and

$$K_B = 2000\zeta \qquad (5)$$

These expressions for K_H and K_B are tabulated in BS 6399:Part 2 and shown in Tables 1 and 2 respectively using accepted values for the damping appropriate to the different forms of construction. Equation 2 can be used if more appropriate values of $\bar{V}_B$, n_o or ζ are available. The resulting graph to determine C_R from K_F is given in Fig 1.

DAMPING

Damping is a function of the material used in the structure, the form and quality of construction, the frequency and the stiffness of the structure. At low amplitudes, damping is provided primarily by the inherent damping of the material. At higher amplitudes, movement at joints provides additional damping through friction, so an all-welded steel structure will provide less damping than one of bolted construction. At large amplitudes, load transfer to cladding and internal walls contributes even more damping, so that damping for ultimate limit state design is higher than for the serviceability limit states.

The value of damping to use at the design stage is extremely difficult to quantify, and may vary significantly between two notionally identical structures. Data have been collected on a wide range of completed buildings and other structures and a reasonable set of damping values can be established for defined classes of structure. This has been incorporated in the tabulated values for K_B given in Table 2.

Table 1 Factor K_H

H (m)	Sea	Country	Town
5	3.5	3.0	2.5
10	5	4.5	4
20	9	8	7
30	12	11	10
50	18	16	14
100	29	27	25
200	50	47	43
300	67	64	60

Terrain types are defined in Part 4

Fig 1 Factor C_R

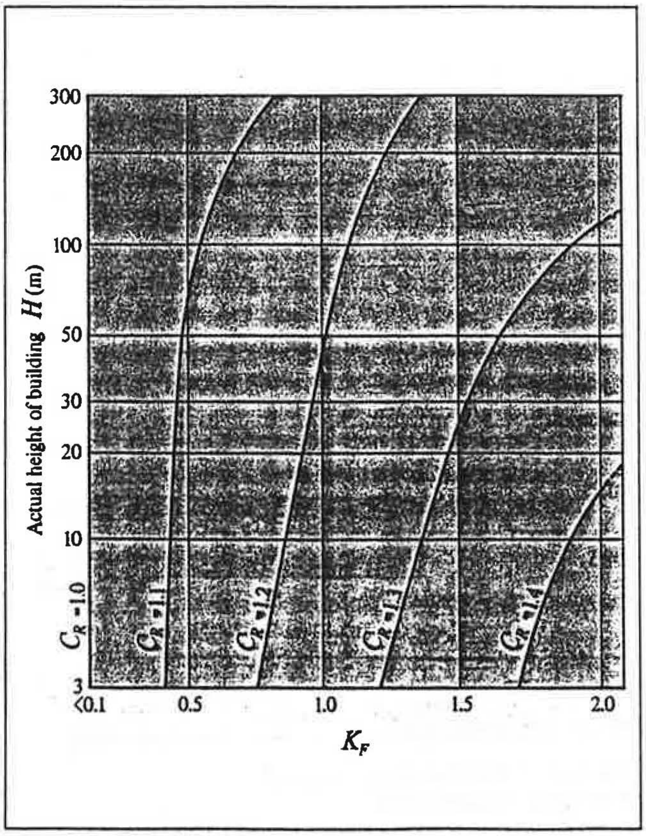

Table 2 Structural damping ratios

Type of building	Factor K_B	Implied damping ratio ζ
Welded steel unclad frames	8	.004
Bolted steel and rc unclad frames, rc chimneys (no lining)	12	.006
Lightly stiffened flexible steel or rc structures; no internal walls	20	.01
Rc core with light cladding; no internal walls	40	.02
Steel and rc frames with structural walls round lifts and stairs only, eg open-plan office buildings	60	.03
Shear wall structures; steel and rc frames with internal and/or external structural shear walls	100	.05
Buildings with structural walls round lifts and stairs and additional masonry walls subdividing floors, eg blocks of flats. All masonry and timber structures	150	.08

FREQUENCY

The calibration procedure is extremely sensitive to the natural frequency of the structure; it is therefore important to be able to assess this parameter as accurately as possible. Unfortunately, at the initial design stage this is not possible so reliance has to be made either on empirical formulae or on the analysis of similar structures.

The most common empirical formula is:

$$n_o = \frac{K}{H}$$

where K is a constant, varying from about 45 to 70
H is the height of the structure in metres.

This works reasonably well for tall structures but is not satisfactory for buildings with a lower aspect ratio. For this reason BS 6399:Part 2 has assumed the form:

$$n_o = \frac{60}{\sqrt{bH}}$$

This produces, generally, a lower bound estimate for n_o and avoids any artificial cut-offs for lower structures for which it works reasonably well.

DYNAMIC ANALYSES

Dynamic response analyses must be undertaken for structures which are extremely sensitive to dynamic effects. The classification procedure provides the limit for which static analyses, augmented by the dynamic magnification factor, are no longer applicable. This is when factor K_F exceeds 2.0, implying a maximum value of C_R of about 1.4.

Dynamic analyses require not only a modal analysis to determine frequencies and mode shapes, but a response analysis in which the wind loading spectrum is defined in terms of the scales and intensities of turbulence, and the structural and aerodynamic damping is assessed. Analytical methods for the response of dynamic structures to wind loading have been published and reference to the documents listed below should be made for guidance. Further advice can be obtained from specialists.

Analytical methods for the response of dynamic structures to wind loading are given in the following documents:

- Engineering Sciences Data, Wind Engineering Sub-series (4 volumes). London, ESDU International.

  NOTE: A comprehensive index covering all items of Engineering Sciences Data is available on request from ESDU International, 27 Corsham Street, London N1. Tel: 01 490 5151.
- Wind engineering in the eighties. London, Construction Industry Research and Information Association. 1981 CIRIA, 6 Storey's Gate, London SW1P 3AU. Tel: 01 222 8891.
- SIMIU, E and SCANLAN, RH. Wind Effects on Structures. New York, John Wiley and Sons, 1978.
- Supplement to the National Building Code of Canada, 1985. NRCC, No 23178. Ottawa, National Research Council of Canada, 1985.

For further reading see Part E

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The assessment of wind loads

Part 3: Wind climate in the United Kingdom

This is the third in a series of Digests which is compatible with the proposed British Standard BS 6399:Part 2. It deals with the derivation of the hourly mean wind speed for sites in the United Kingdom. This site wind speed is then used in Part 4 of the Digest as the basis for the appropriate wind speeds to be used for the structure to be designed.

BASIC WIND SPEED

The Meteorological Office records the hourly mean wind speeds and maximum gust speeds each hour at stations throughout the UK. Previous analyses only used the maximum speeds each year for which records were available, but recent analysis of these data extracts the maximum wind speed from every individual storm. This increases greatly the data available for analysis.

Recent analyses by BRE also adopted a more accurate model than that used previously to derive the required extreme wind speeds to be used for structural design. This has resulted in the wind speed map in Figure 1. It gives the basic maximum hourly mean wind speed $\overline{V}_B$ as isopleths, at 10 m above ground at sea level, adjusted for standard 'country' terrain. $\overline{V}_B$ has an annual probability of exceedance of 0.02, irrespective of direction, and was previously referred to as the 50-year return period wind speed. The notion of 'return periods' however has caused confusion with designers so this form of definition has been abandoned in favour of annual probability.

$\overline{V}_B$ must be adjusted for altitude and direction and, for structures of limited sub-annual periods of exposure, for seasonal effects. These adjustments provide the hourly mean wind speed appropriate to the site at 10 m above standard terrain.

The hourly mean site wind speed $\overline{V}_{SITE}$ for any specific direction is given by:

$$\overline{V}_{SITE} = \overline{V}_B \times S_{ALT} \times S_{DIR} \times S_{TEM}$$

where $\overline{V}_B$ is the basic wind speed

S_{ALT} is an altitude factor

S_{DIR} is a direction factor

S_{TEM} is a seasonal building factor

The statistical factor S_3 in CP3 chapter V:Part 2 is no longer needed because adjustment for risk is made by the partial factors for temporary and permanent structures. The other S factors in CP3 are replaced by equivalent factors in Parts 3 and 4 of this Digest.

Adjustments for the actual site terrain together with the derivation of the appropriate gust speed to be used in the design of static and mildly dynamic structures (see Part 2) are then described in Part 4. Allowance for the effects of topography, if relevant, can be made using the procedures described in Part 5.

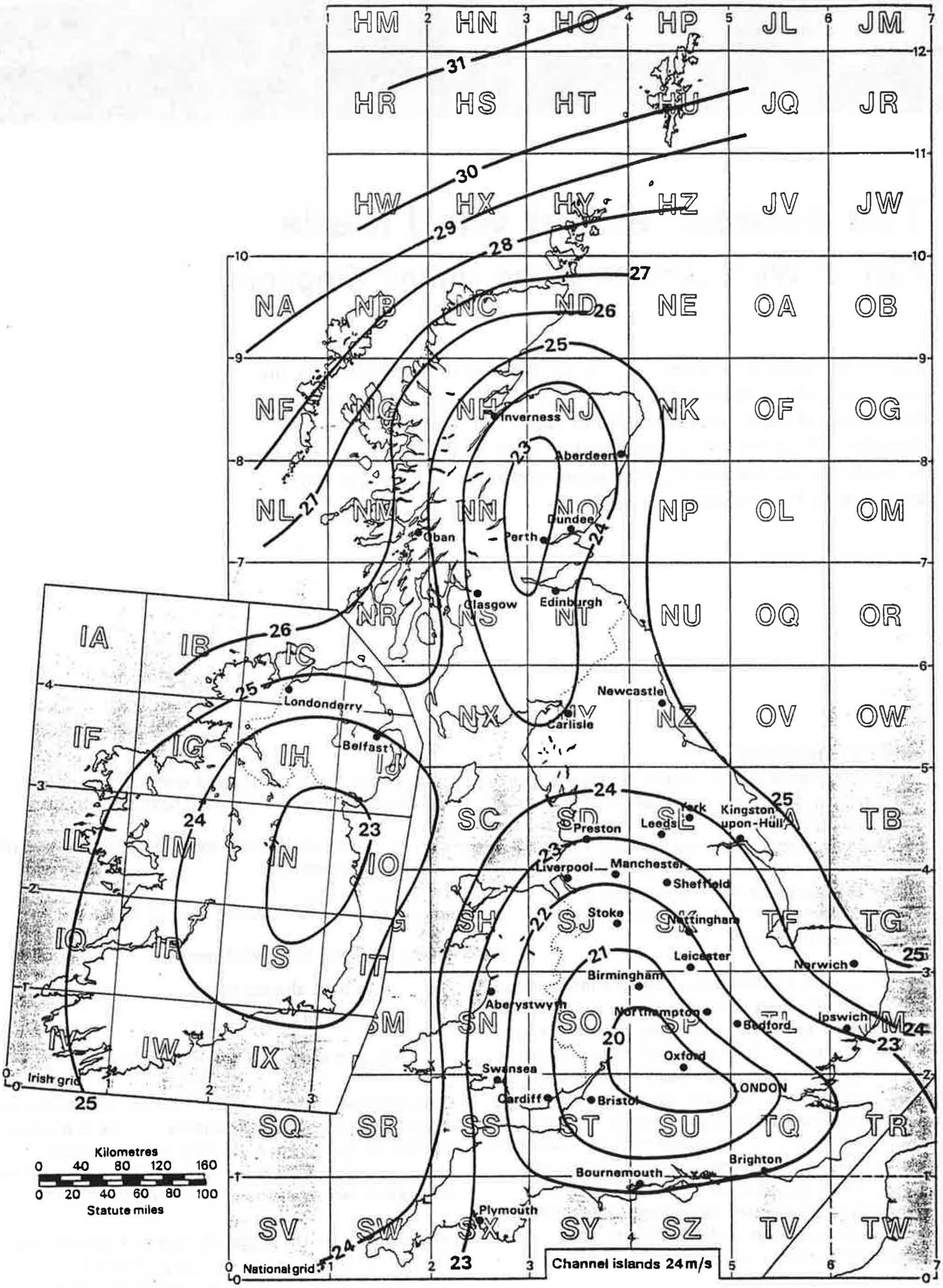

Fig 1 Map of the United Kingdom showing the reference basic hourly mean wind speed in metres per second

ALTITUDE FACTOR S_{ALT}

The analyses of the wind data from the Meteorological Office records show a dependence on site altitude. The analyzed data are, therefore, adjusted such that the wind speed map shown in Figure 1 is related to 10 m above the ground at sea level.

To derive the wind speed for any site at altitude A in metres above mean sea level, an adjustment of 10% per 100 m of altitude must be made to the basic wind speed from the map.

Therefore $S_{ALT} = 1 + 0.001A$

This correction accounts only for the effect of large-scale, slowly changing topography. The effects of rapid topographic changes (hills, cliffs and escarpments etc) are dealt with separately by the topography factor (see Part 5).

For guidance, a topography factor will need to be included in deriving the appropriate wind speed for design when the upwind slope is in excess of 0.05. In all other cases, the altitude factor accounts for the site level — see Figure 2.

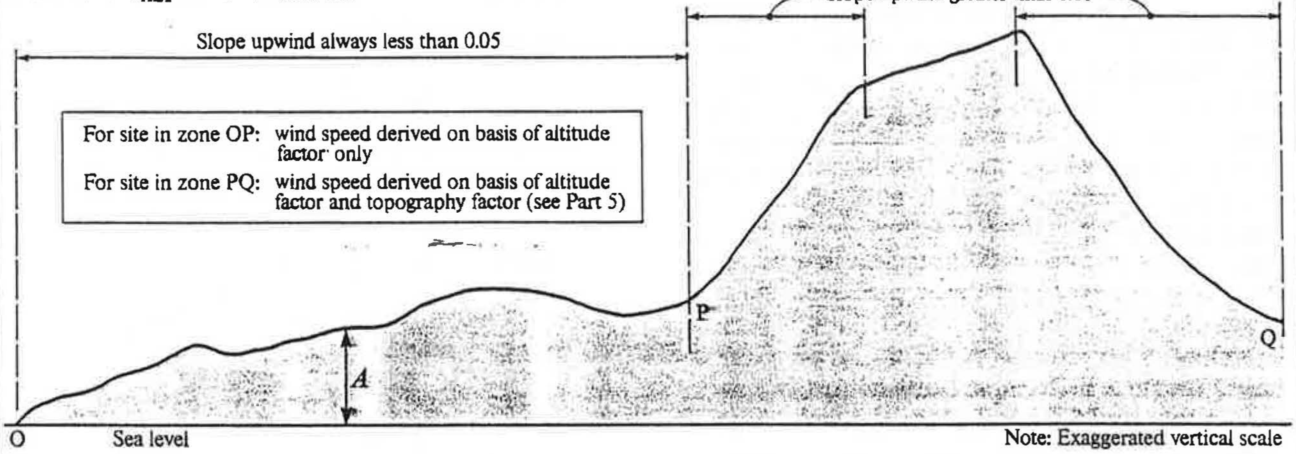

Fig 2 Use of the altitude factor

DIRECTION FACTOR S_{DIR}

The directional characteristics of extreme winds in the United Kingdom, used for design purposes, show no significant variation with location, so the directional factor is a function of the wind direction only. The highest winds come from the directions of the prevailing winds, between south-west and west. The directional extreme factor determined by direction approaches the value of the all-direction factor (strictly the value irrespective of direction) for winds from these directions. If directional factors were adopted on the basis that the annual risk in a given direction were 0.02 the overall risk from all directions would be greater owing to the contributions from other directions. Further analysis was necessary to derive the direction factors which are plotted in Figure 3; it can be seen that values greater than unity are obtained for the prevailing wind direction, but less than unity elsewhere in order to keep the overall risk at the 0.02 level. It is these factors which have been incorporated as the directional factor S_{DIR} and which are tabulated in Table 1.

The factors apply to 30° sectors; for intermediate directions values can be interpolated. Account should be taken of any uncertainty in the orientation of the building at the design stage; for those buildings or components which may be sited in any orientation a factor of 1.05 must be applied.

Table 1 Direction factor

Wind Direction:	N			E			S			W		
°True:	0	30	60	90	120	150	180	210	240	270	300	330
S_{DIR}	0.81	0.76	0.76	0.77	0.76	0.83	0.89	0.97	1.05	1.04	0.95	0.86

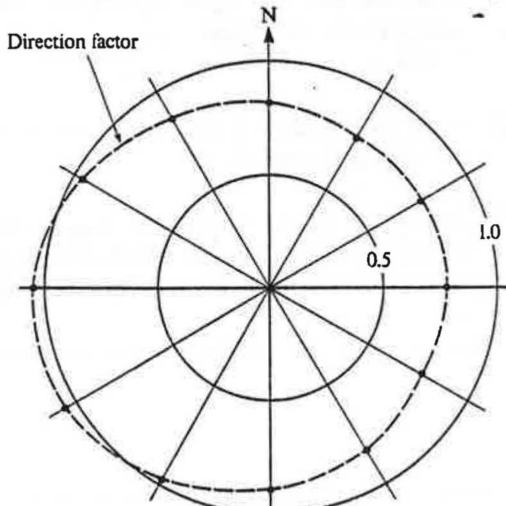

Fig 3 Direction factor

SEASONAL FACTOR S_{TEMP}

The highest extreme winds in the UK are expected in December and January. In the summer months of June and July winds may be expected to be only about 65% of these highest extremes. Structures which are expected to be exposed only in these more favourable conditions could be designed for a lower wind speed whilst maintaining the same risk of exceedance.

Typical of these applications are temporary structures: marquees, buildings erected solely for summer events (such as sporting fixtures) and buildings under construction. Generally, the structure will not be exposed for more than one season so that the seasonal factor needs to be used with a lower partial safety factor appropriate to temporary structures, to achieve consistent reliability. However, there are instances when a structure will be erected during the same short period over a number of years (a marquee for an annual event being an ideal example); in this case, the seasonal factor is used with the appropriate partial safety factors as though it were a permanent building.

The values of the seasonal factor, S_{TEMP}, are given in Table 2 for three different sub-annual periods: one, two and four-month periods. They are appropriate throughout the United Kingdom. To use the one-month values, it is necessary to have confidence in the building programme, or in the repeatability of the annual event. For example, a structure designed with a seasonal factor for August of 0.71 would, for the same reliability, be exposed to a 33% increase in loading if its construction or use were delayed to September. Factors for the six-month summer and winter periods are also shown in Table 2. No advantage is given by this factor if the building is to be erected or in use at least during the two-month period of December and January.

Table 2 Values of S_{TEM}

Sub-annual periods			
1 month	2 months	4 months	
Jan 0.98	Jan) to) 0.98	Jan) to) 0.98	
Feb 0.83	Feb) to) 0.86	Apr)	Feb) to) 0.87
Mar 0.82	Mar) to) 0.83	Mar) to) 0.83	May)
Apr 0.75	Apr) to) 0.75	Jun)	Apr) to) 0.76
May 0.69	May) to) 0.71	May) to) 0.73	Jul)
Jun 0.66	Jun) to) 0.67	Aug)	Jun) to) 0.83
Jul 0.62	Jul) to) 0.71	Jul) to) 0.86	Sep)
Aug 0.71	Aug) to) 0.82	Oct)	Aug) to) 0.90
Sep 0.82	Sep) to) 0.85	Sep) to) 0.96	Nov)
Oct 0.82	Oct) to) 0.89	Dec)	Oct) to) 1.00
Nov 0.88	Nov) to) 0.95	Nov) to) 1.00	Jan)
Dec 0.94	Dec) to) 1.00 Jan)	Feb)	Dec) to) 0.98 Mar)

The factor for the six-month winter period October to March inclusive is 1.0, and for the six-month summer period April to September inclusive is 0.84.

PROCEDURE

To derive the site hourly mean wind speed:

(1) From the location of the site determine the basic hourly mean wind speed, $\bar{V}_B$, from the map in Figure 1.

(2) From the altitude of the site (in metres) determine the altitude factor S_{ALT}.

(3) Determine the direction factor S_{DIR} for each wind direction to be considered. For a building which may be sited in any orientation S_{DIR} is taken as 1.05.

(4) For seasonal or temporary structures determine the seasonal factor S_{TEMP}. Note the sensitivity of this factor and only use values less than 1.0 if it is certain that the building will be exposed only for the specified sub-annual periods.

(5) Calculate the site hourly mean wind speed for each direction from:

$$\bar{V}_{SITE} = \bar{V}_B \times S_{ALT} \times S_{DIR} \times S_{TEMP}$$

For further reading see Part 2

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The assessment of wind loads

Part 4: Terrain and building factors and gust peak factors

This Digest is the fourth in a series which is compatible with the proposed British Standard BS 6399:Part 2. It uses the 'full' method of the British Standard to derive the appropriate gust wind speeds to be used for the design ~~of~~ 'static and mildly dynamic' structures (as defined in Part 2) from the site hourly mean wind speed (derived in Part 3). A more accurate assessment of gust speeds can be obtained from the use of the BRE computer program *STRONGBLOW*.

DERIVATION OF REFERENCE WIND SPEEDS TO BE USED FOR DESIGN

Having selected the appropriate basic speed from the wind map, and taken due account of the site's altitude and wind direction, the hourly mean site speed $\overline{V}_{SITE}$ can be derived (see Part 3). This speed must be adjusted further to account for the terrain of the site and for the height above ground for which the wind speed is required. In addition, the appropriate gust speed needs to be used for the design of static and mildly dynamic structures (see Part 2). These parameters can be accounted for by the use of further S factors so that the reference wind speed V_{REF} at any height can be derived, for sites in country terrain, from:

$$V_{REF} = \overline{V}_{SITE} S_{TB} \qquad (1)$$

where S_{TB} is the terrain and building factor given by:

$$S_{TB} = S_{SC}(1 + g_{GUST} S_{TSC} + S_{TOP}) \qquad (2)$$

This factor combines the roles of factors S_1 and S_2 in CP3 Chapter V: Part 2.

For sites in town terrain the above factors S_{SC} and S_{TSC} are modified by two further factors resulting in, for town sites,

$$S_{TB} = S_{SC} S_{CT}(1 + g_{GUST} S_{TSC} S_{TCT} + S_{TOP}) \qquad (3)$$

BS 6399: Part 2 includes a simplified procedure for use with common structures which allows S_{TB} to be obtained directly from tables.

The following factors are described later:

S_{SC} and S_{CT} are fetch factors which modify the hourly mean wind speed to take account of the terrain of the site.

S_{TSC} and S_{TCT} are turbulence factors which modify the turbulence effects to take account of the terrain of the site.

g_{GUST} is a gust peak factor.

S_{TOP} is the topography factor described in Part 5.

S_{TOP} is an increment to be added in equations (2) and (3) to derive the factor S_{TB}. In this respect it is different from the factor S_1 (described in CP3 Chapter V: Part 2) which was a multiplying factor to apply to the wind speed to account for topographical effects.

Building Research Establishment
DEPARTMENT OF THE ENVIRONMENT

Technical enquiries to:
Building Research Establishment
Garston Watford WD2 7JR
Telex 923220 Fax 664010

TERRAIN CATEGORIES

The roughness of the ground surface controls both the mean wind speed and its turbulent characteristics. The wind speed is higher near the ground over a smooth surface, such as open country, than over a rougher surface, such as a town. By defining three basic terrain categories wind speeds can be derived accounting for the influence of upstream categories different from that of the site. These three basic categories are:

Sea This applies to any offshore location and to inland lakes of at least 5 km upstream of the site. Such a category must also be defined so that the gradual deceleration of the wind speed inland from the coast can be quantified for any land-based site.

Country This covers a wide range of terrain, from the flat, open, level or nearly level country with no shelter (fens, airfields, moorland or farmland with no hedges or walls), to undulating countryside with obstructions, such as occasional buildings and windbreaks of trees, hedges or walls.

Town Town terrain includes suburban regions in which the general level of roof tops is about 5 m above ground level (all two-storey housing) provided that such buildings are at least as dense as normal suburban developments for at least 100 m upwind of the site. Whilst it is not easy to quantify, it is expected that the plan area of the buildings is at least 8% of the total area over that 100 m and within a 30° sector of the site — see Fig 1.

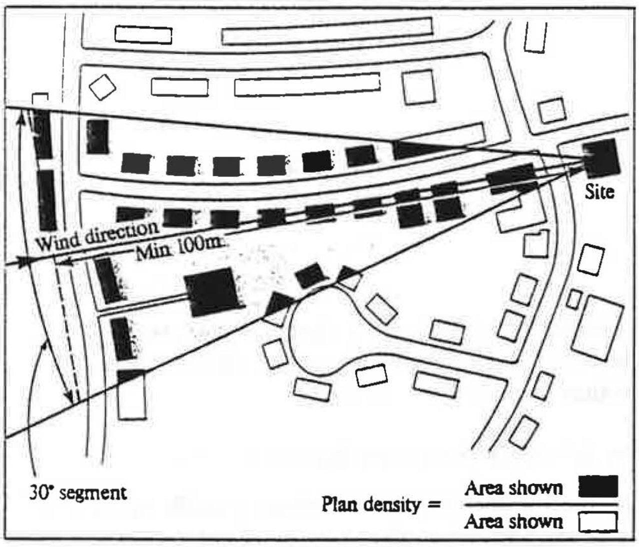


Fig 1 Typical town site

Variation of fetch

Fetch refers to the terrain directly upwind of the site. The adjustment of wind speed characteristics as the wind flows from one terrain to another is not instantaneous. At a change from a smooth to a rougher surface the wind speed is gradually slowed near the ground.

This adjustment requires time to work up through the wind profile; at any site downwind of a change in terrain the mean speed lies between that for the smooth terrain and that for the fully developed rough terrain. This is shown diagrammatically in Fig 2.

This gradual deceleration of the mean speed is accounted for by defining the site by its distance downwind from the coast and, if it is in a town, as its distance from the edge of the town.

Shelter of a site from a upwind town has not been allowed for in the procedures in these Digests, other than if the site is in a town itself. To do so would introduce too much complexity with only a marginal saving in the resulting wind loads. The BRE computer program *STRONGBLOW* can be used to account for such effects.

It can be seen that by introducing the location of a site with respect to its distance from the sea and, if relevant, its distance from the edge of a town, different wind speeds will be obtained from different directions. For the site shown in Fig 3 a southerly wind will pass over country (AB) and town (BO) causing some deceleration of the wind. A westerly wind will be slowed down more because CD is greater than AB and DO is greater than BO.

In the example given in Fig 3, the direction factor S_{DIR} produces higher basic winds from the west ($S_{DIR} = 1.04$) than the south ($S_{DIR} = 0.89$); in this case the site wind speeds for these two directions may not be significantly different. However, an easterly wind would be markedly lower as both the direction factor and the effects of fetch changes would decrease the wind speed.

It is important, if directional effects need to be considered, to take full account of both the effects of terrain upwind of the site and the direction factor. This becomes even more significant if the effects of topography need to be considerd: the topography factor S_{TOP} will have a major influence on the value and the direction of the most critical wind speed.

Fetch and turbulence factors

Sites in country terrain

To account for the effects of terrain on the hourly mean wind speed, a set of fetch factors S_{SC} has been defined; these factor the hourly mean site wind speed $\overline{V}_{SITE}$ to obtain the hourly mean wind speed at any height above ground for a site in country terrain at various distances from the sea. This is the term outside the brackets in equation (2). However, as the designer is concerned with the appropriate gust wind speed in assessing static and mildly dynamic structures, equation (2) incorporates the appropriate factors to do this.

Fig 2 Variation of fetch

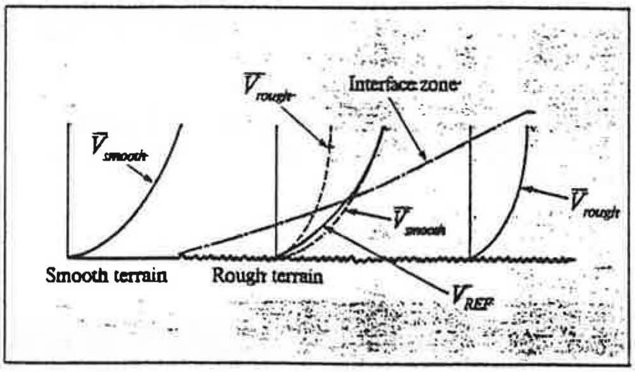


Table 1

Factors S_{SC} and S_{TSC}								
		Distance from site to sea (km)						
Effective height H_{EFF} (m)	Factor	0.1	0.3	1.0	2.0	10	30	100 or more
2 or less	S_{SC}	.873	.840	.812	.792	.774	.761	.749
	S_{TSC}	.203	.215	.215	.215	.215	.215	.215
5	S_{SC}	1.06	1.02	.990	.966	.944	.928	.913
	S_{TSC}	.161	.179	.192	.192	.192	.192	.192
10	S_{SC}	1.21	1.17	1.13	1.10	1.07	1.06	1.04
	S_{TSC}	.137	.154	.169	.175	.178	.178	.178
20	S_{SC}	1.32	1.31	1.27	1.23	1.21	1.19	1.17
	S_{TSC}	.127	.132	.145	.157	.163	.164	.164
30	S_{SC}	1.39	1.39	1.35	1.31	1.28	1.26	1.24
	S_{TSC}	.120	.122	.132	.145	.155	.159	.159
50	S_{SC}	1.47	1.47	1.46	1.42	1.39	1.36	1.34
	S_{TSC}	.112	.113	.117	.125	.135	.145	.147
100	S_{SC}	1.59	1.59	1.59	1.57	1.54	1.51	1.48
	S_{TSC}	.097	.100	.100	.100	.110	.120	.126
200	S_{SC}	1.74	1.74	1.74	1.73	1.70	1.67	1.65
	S_{TSC}	.075	.075	.075	.078	.083	.093	.095
300	S_{SC}	1.84	1.84	1.84	1.83	1.82	1.78	1.76
	S_{TSC}	.065	.065	.065	.067	.068	.080	.081

Note: Interpolation may be used

Table 2

Adjustment Factors S_{CT} and S_{TCT} for sites in 'town' terrain							
		Distance from site to edge of town (km)					
Effective height H_{EFF} (m)	Factor	0.1	0.3	1.0	3.0	10	30 or more
2 or less	S_{CT}	.695	.653	.619	.596	.576	.562
	S_{TCT}	1.93	1.93	1.93	1.93	1.93	1.93
5	S_{CT}	.846	.795	.754	.725	.701	.684
	S_{TCT}	1.47	1.61	1.63	1.63	1.63	1.63
10	S_{CT}	.929	.873	.828	.796	.770	.751
	S_{TCT}	1.18	1.39	1.51	1.52	1.52	1.52
20	S_{CT}	.984	.935	.886	.853	.824	.804
	S_{TCT}	1.00	1.17	1.35	1.44	1.45	1.45
30	S_{CT}	.984	.965	.915	.880	.851	.830
	S_{TCT}	1.00	1.07	1.25	1.38	1.43	1.43
50	S_{CT}	.984	.984	.947	.912	.881	.859
	S_{TCT}	1.00	1.00	1.14	1.28	1.38	1.42
100	S_{CT}	.984	.984	.984	.948	.917	.894
	S_{TCT}	1.00	1.00	1.00	1.14	1.28	1.38
200	S_{CT}	.984	.984	.984	.980	.947	.924
	S_{TCT}	1.00	1.00	1.00	1.07	1.19	1.31
300	S_{CT}	.984	.984	.984	.984	.964	.940
	S_{TCT}	1.00	1.00	1.00	1.04	1.14	1.24

Note: Interpolation may be used

The turbulence factor S_{TSC} depends on the same parameters as the fetch factor, for example effective height of the building and the site terrain. These are combined in Table 1.

The gust peak factor g_{GUST} is dependent on the size of the structure and, for practical purposes, is independent of the terrain. It can, therefore, be defined separately as described later.

Sites in town terrain

To account for the further decelerating effect of the mean wind speed for sites in towns, an adjustment fetch factor S_{CT} is used; it is always less than unity. Similarly, to account for the increased turbulence over rougher town terrain, an adjustment turbulence factor S_{TCT} is used; this is always greater than unity. These factors are shown in Table 2, related to the distance of the site from the edge of the town and the effective height of the building.

Effective height

In rough terrain, such as towns and cities, the wind tends to skip over the buildings at, or below, roof top level, leaving sheltered regions below. The height of this sheltered zone is a function of the area density of the buildings and the general height of the obstructions. The effective height of any building H_{EFF} in such terrain is the actual building height, H, less the height of the sheltered zone. An empirical formula given by:

$$H_{EFF} = H - 0.8\, H_{OBS} \text{ or } H_{EFF} = 0.4\, H_{OBS} \quad (4)$$

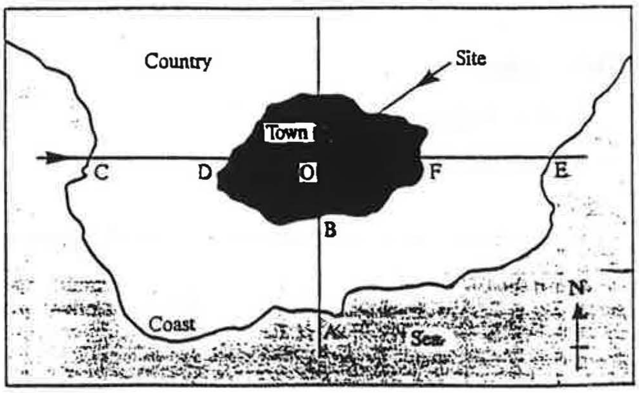
whichever is the greater

has been shown to correlate well with available data, taking H_{OBS} to be 5 m where buildings are generally two to three storeys high and 15 m where buildings are at least three storeys high.

However, this provides negative or very small values of H_{EFF} for low buildings surrounded by higher buildings and so a minimum value of 0.4 H_{OBS} has been proposed to account for this situation.

In towns where there is an open area upwind of the building, extending at least twice the structure's height (buildings facing open parkland), there will be minimal shelter and the effective height should be taken as the actual height, H, of the building.

Fig 3 Effects of terrain



GUST PEAK FACTOR

A simplified formula for g_{GUST} given by

$$g_{GUST} = 0.42 \ln (3600/t) \quad \text{.............. (5)}$$

where t is the gust duration time in seconds has been shown to be within a few percent of more complex formulations. For the purposes of these procedures, the simplified formula was considered quite adequate. However, it is a factor dependent on the gust duration, t, which is not of direct interest to the designer. His concern is to choose, for static structures, the appropriate gust speed which will envelop his structure or component to produce the maximum loading.

Fortunately for bluff type structures, such as buildings, which can be designed statically, there is a simple empirical relationship between the duration, t, and the size of the structure or element, t, given by:

$$t = \frac{4.5b}{\overline{V}} \quad \text{.............................. (6)}$$

where $\overline{V}$ is the relevant mean wind speed given by S_{SC} $\overline{V}_{SITE}$ for country and S_{SC} S_{CT} $\overline{V}_{SITE}$ for town and where b is the diagonal dimension of the loaded area under consideration. This may be the whole building, a single cladding element or any intermediate part.

By combining equations 5 and 6, a graph can be plotted of height against size to give values of the gust peak factor g_{GUST} — see Fig 4. For design purposes it is likely that $\overline{V}_{SITE}$ will lie within the range 20 to 30 m/s so that for a typical b = 20 m, g_{GUST} varies from about 2.86 to 3.0. This variation of g_{GUST} makes only about a 20% difference in the resulting gust speeds. Consequently, for these purposes the values of g_{GUST} adopted have been based on a $\overline{V}_{SITE}$ fixed at 25 m/s. The resulting values of size, b, are then shown as the abscissa on the graph of Fig 4 which enables g_{GUST} to be read directly for given heights and sizes.

Factor g_{GUST} is given in BS 6399:Part 2 in a table for various heights and sizes of loaded area.

CLASSIFICATION PROCEDURE

The conventional gust factor S_G which is required for the full classification method is the ratio of the gust and the mean wind speeds given by:

$$S_G = \frac{1 + g_{GUST} S_{TSC} S_{TCT} + S_{TOP}}{1 + S_{TOP}} \quad (7)$$

This reduces to:

$$S_G = 1 + g_{GUST} S_{TSC} S_{TCT}$$

where topography is insignificant.

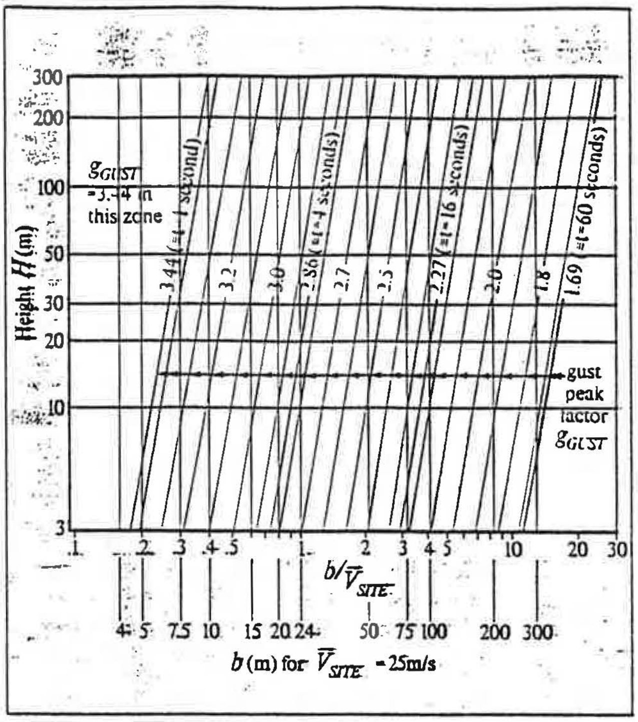


Fig 4 Gust peak factor

For further reading see Part 1

PROCEDURE

To derive the reference wind speed:

(1) From Part 3, determine the site hourly mean wind speed for each wind direction to be considered.

(2) From Table 1, determine factors S_{SC} and S_{TSC} for the site according to its distance from the sea in the upwind direction and building height.

(3) For sites in towns determine factors S_{CT} and S_{TCT} according to the upwind distance of the site from the edge of the town and the effective height, H_{EFF}.

(4) For sites affected by topography, from Part 5 calculate S_{TOP} appropriate to the wind direction being considered.

(5) Determine S_{TB} from equation (2) for sites in country and Equation (3) for sites in town.

(6) Determine V_{REF} from equation (1).

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