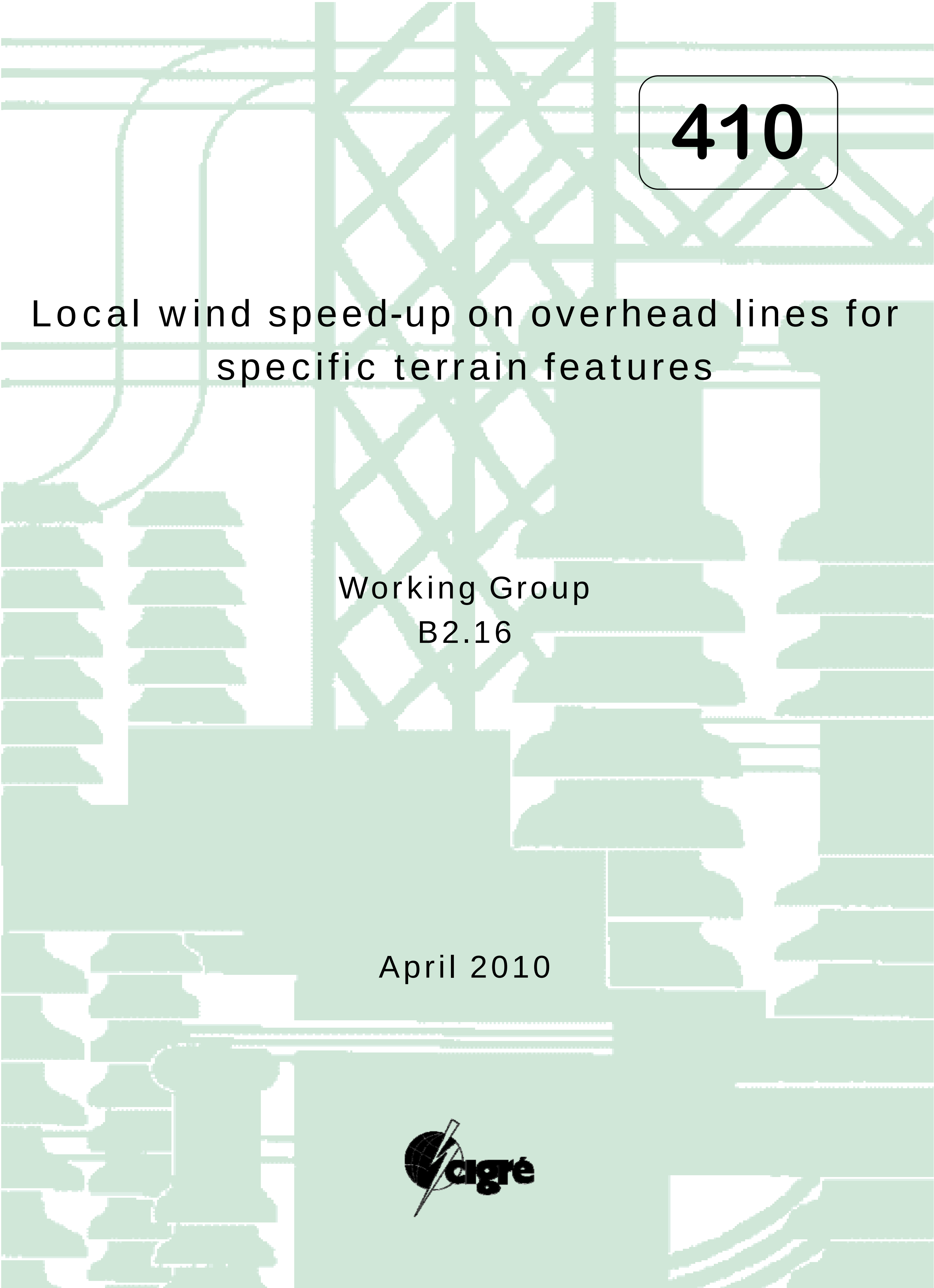

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Local wind speed-up on overhead lines for specific terrain features

Working Group
B2.16

April 2010

Local Wind Speed-Up on Overhead Lines for Specific Terrain Features

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ISBN: 978-2-85873-097-1

1 Introduction

1.1 Standard Wind Codes

Standard codes for wind engineering and design of structures include wind dependencies with respect to general variations in the overall terrain roughness, as well as some general rules for speed-up of winds over hills and escarpments. Such codes cover the general needs concerning wind engineering for overhead power lines as well as other structures.

There are however limitations for the application of these general rules for treating extreme terrain roughness, predominate hill forms and escarpments. In particular this relates to countries characterised by high winds that pass over rugged terrain such as many high hills, mountains, valleys and fjords before impacting on overhead line construction. The introduction of probabilistic methods as given by IEC 60826 [2] has encouraged more detailed and precise knowledge about the various phenomena influencing the overhead lines. These affect overhead power lines in the wide varieties of topography and climate they are subject to.

When selecting the category for terrain roughness [2], the terrain is considered homogeneous over relatively large areas, up to 10 km or more, in all directions. Hills and escarpments are also considered to be regular in shape and 2-dimensional with infinite length. This is not always the case for practical applications.

1.2 Wind Effects over variable local terrain

Most standard wind codes do not include effects on wind speeds in more varying terrain where the roughness characteristics change significantly over short distances relevant to the scale of an overhead line span. Such wind codes also do not include topographic generated features such as

- corner effects along the foot of mountains and hills
- funnelling effects in valleys or in between hills
- vortex formation behind steep terrain
- other effects that may cause significantly increased wind speeds in the local terrain.

Such topographic features may have length scales ranging from a few tens of metres up to several km.

As far as is known, only two countries take such effects into account to some extent in their wind codes, namely New Zealand [4] and Norway [14]. The New Zealand code covers the general strengthening of winds in the lee of the Southern Alps and Central North Island, whilst the Norwegian code identifies individual topographical properties generating higher winds.

1.3 Wind phenomena and line failures

It is outside the scope of this document to describe all these phenomena in detail, as many of them are well described in textbooks in for instance mountain meteorology. However, experiences from overhead line failures and damage to buildings and other structures during the last decades have revealed that many of them were neither known nor taken into account by designing engineers. This document describes some of these phenomena, however, in various levels of detail, with specific examples.

Wind phenomena described in this document are known from many countries, for instance Japan, New Zealand, Iceland, Norway and others, however scarcely reported in literature. The Australia and New Zealand Wind Code is however taking some special phenomena into account in mountainous terrain above 500 m above sea level (asl).

In the design phase it is not possible, nor appropriate, to incorporate thorough analyses of the topography and all its possible effects on local wind conditions along the route of an overhead line. However, it may be useful to check some potentially exposed points of the line in order to validate or adjust the design wind speed in certain places.

In the case of failure events, it may also be useful to perform retrospective analyses of wind conditions during particular storm events, and thus understand better the reason for wind-induced failures. Failure investigators need to be careful to identify the initiating failure mechanism and its associated cause. It could be related to significant physical terrain features up to several kilometres upwind of the failure site.

1.4 Document scope

This document therefore focuses on mountainous and hilly terrain where standard wind codes are seldom fully applicable due to the presence of predominant topographical features.

Even in lowlands on the downwind side of hills and mountains, the properties of the wind turbulence may be totally determined by the mechanical and thermal stresses on the atmospheric boundary layer introduced by the roughness and heights of the mountains or other significant topographical features. As such properties of the airflow may be conserved over long distances downwind, they should be accounted for in any building project where the influence of wind has economic importance.

The scope of this document is to identify such terrain and to provide guidelines for how local wind speeds can be evaluated in such places where the wind forces acting on an overhead line may be significantly higher in specific sections. It is restricted to predominating mountain features, sharp hills or escarpments up to a few hundred metres above the surrounding terrain. Some of the methodology described in this document was developed in connection with a revision of the recent Norwegian Building Code, NS3491-4 (wind loads) (2002) [14]. Some of the standard Code material is included here to demonstrate how the method is applied for such purposes.

As different wind codes are applied in this document the careful reader may note some minor discrepancies in gust factors etc., when comparing with e.g. IEC 60826. These reflect however an uncertainty less than 10 % and therefore less than the variations that normally occur in natural wind in ordinary topography.

1.5 High Intensity winds

Cigré WGB2.16 published in 2004 the Technical Brochure No 256 “Current practices regarding frequencies and magnitudes of high intensity winds” [19]. The TB256 focuses on various meteorological phenomena causing high wind speeds. Those effects may hit an overhead line in random places, whereas the present document focuses on more site-specific phenomena. It is the aim of WGB2.16 that both of these documents will provide an improved tool to estimate and validate design wind conditions for overhead power lines.

It should also be noted that neither the high intensity wind effects described in [19] nor the site-specific effects described in this document, belong to the same statistical population of general wind data used as the basis for extreme wind speed assessments by national authorities. Therefore it is important to consider such effects as to be superimposed on the general design wind speeds.

1.6 Acknowledgements

Cigré WGB2.16 acknowledges Standards Norway (SN) and Dr. Knut Harstveit, of the Norwegian Meteorological Institute, for their permissions to implement this material into this Cigré document.

The consulting company Jøsok Prosjekt AS, Bergen, Norway, has very generously given their permission to use one of their power line projects for the application example given in Appendix 1.

WGB2.16 also acknowledges the reviewers, Mr Koji Fukami, in collaboration with Mr Yukichi Sakamoto, Japan, and Mr. R. Lake, New Zealand, for their valuable comments and input to improve this document.

2 Examples of terrain influenced winds

2.1 General aspects of wind and turbulence

Wind is a result of large and small scale pressure differences within the atmosphere over the surface of the Earth. Such pressure differences arise from temperature differences between the Equatorial and Polar Regions, between oceans and continents and down to small scale temperature gradients from many causes over the land surface. Consequently, mechanical shear forces arise from lateral and vertical differences in air velocities within the airflows, and turbulent variations in wind speed and direction occur. Whilst the boundary condition implies that the wind speed is always zero at the ground surface, the wind speed just above the ground varies very significantly due to inhomogeneous topography. The internal turbulence and composition of vortices may therefore be quite intense, especially in mountainous regions where peaks and steep mountain sides are frequent.

Although such topography in general reduces the main wind speed on the leeward side, it may in some cases increase the wind gusts to unexpectedly high values in certain situations.

Enhancements of local winds are often found in places like:

- over hill crests
- near sharp edges (escarpments) exposed to high level winds over surrounding terrain
- behind elongated mountains (rotor formation)
- behind steep mountain sides (or edges) where particular turbulence may be formed (vortex “streets”).
- on the side of hills and mountains (corner effect)
- in valleys (including converging mountains) or fjords where the airflow may be compressed locally (funnelling effect)
- katabatic winds like föhn and bora
- etc.

The wind enhancement over hill crests and escarpments are generally implemented in standard wind codes (see section 2.3). These phenomena are based on mechanical flow patterns.

Aerodynamical phenomena such as rotors and vortex shedding (streets) are generally not considered in wind codes, although their magnitude may be very substantial. As there is a new understanding of such phenomena they are the main focus of this document. Two examples are mentioned in section 2.4 and a practical approach to quantify these is given in Appendix A.

Chapter 4 describes other wind enhancement effects which are also influenced by topography. These are handled by some National codes according to local requirements. They are not further considered here.

Various sheltering effects and general wind phenomena normally treated in standard wind codes are only discussed here as much as it may be necessary for the understanding of the main topics of this report.

2.2 Davenport study of typhoon Ellen in Hong Kong

The first known example in the literature of a devastating effect from small-scale topography on a transmission line is from Hong Kong (A. Davenport [5]). A tropical storm (named "Ellen") damaged a 400 kV transmission line in September, 1983. The damage was however restricted to a few towers. As a whole, the design criteria, where a wind model for hillcrests was included, proved to be adequate for this area, see Figure 2.1. The damage occurred on the lower part of some specific towers. Davenport found that both the small-scale topography as well as internal resonance and vibration phenomena affected the towers.

The conclusions from the Davenport study were:

1) The footings of several towers were founded on local prominent rock piles. Although they were not distinguished as part of the large-scale terrain features, they nevertheless strongly accelerated the flow near the base of the towers. This is illustrated in the right part of Figure 2.1.
2) The dimensions of the lower plan bracing in the tower and the actual wind speed coincided in such a way that a vibration was induced in the bracing, leading to breakage of bracing members, see Figure 2.2
3) Another resonance phenomenon appearing from the "Ellen" event was that bolts had loosened due to vibration of some longer angle members, where one angle leg was pointing at a small angle against the wind.

Effect 1) is a result of small scale local topography, whilst 2) and 3) are resonance phenomena that should be taken into account also in flat terrain.

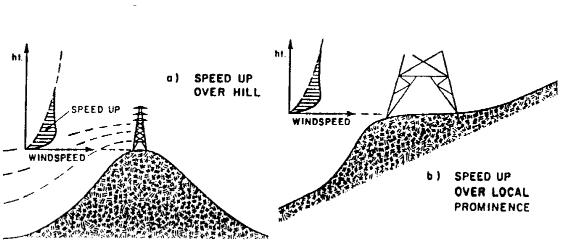


Figure 2.1 Illustrations of large and small scale wind speed-up effects in hilly terrain [5].

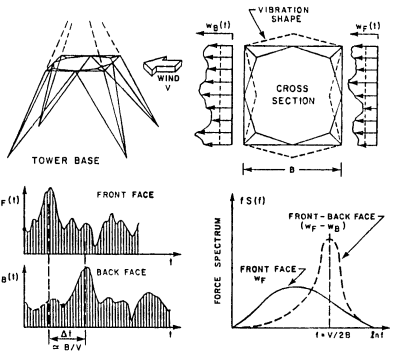


Figure 2.2 Convective amplification of wind loads on the plan bracing of a transmission tower [5].

Several studies were initiated relating to the particular wind climate in the Hong Kong area when such interactions of high intensity winds and topographical features were revealed. This resulted in a new codification of wind loading in the area based on wind tunnel studies as well as numerical simulations [6].

2.3 Local wind speed-up over hills

Standard wind codes include the effect of wind enhancements over smooth hilltops or on top of escarpments. Such hills are typically generalised to Gaussian or cosine shapes. Taylor [1] showed that these speed-ups can double the wind speed and hence the wind pressure with a factor of 4. Effects of this kind are not included directly in [2], but they are incorporated in most wind codes, such as ASCE [3], AS/NZS 1170-2 2002 [4].

Figures 2.3 to 2.5 are taken from [4] and shows areas for wind enhancements over hills (2-3) and escarpments (2-4). The characteristic shapes of the wind profile over such areas are also shown.

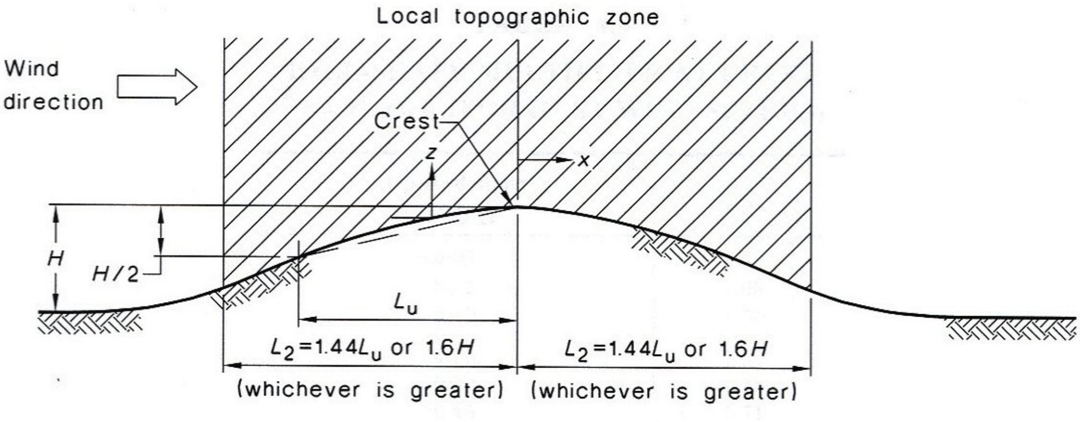
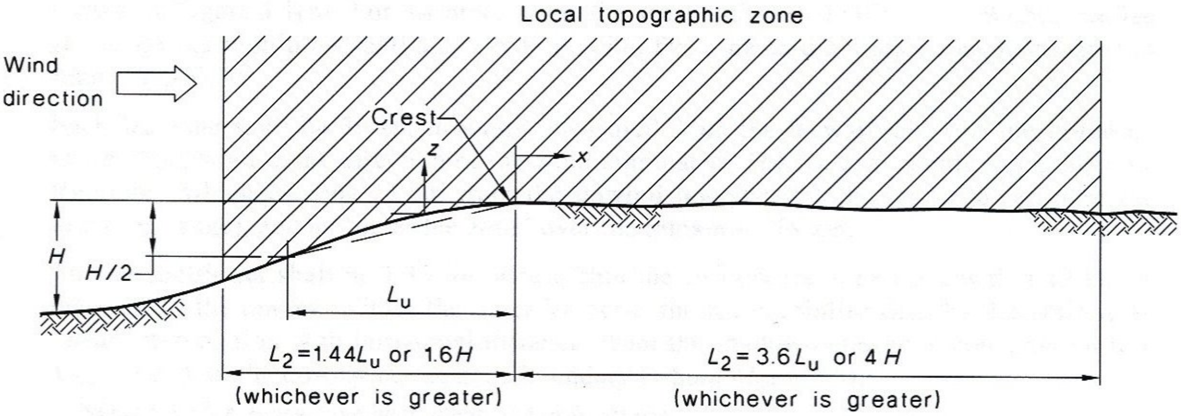


Figure 2.3 Wind over a hill [4].



NOTE: For escarpments, the average downwind slope, measured from the crest to a distance of the greater of 3.6 L_u or 4 H shall not exceed 0.05.

Figure 2.4 Wind over escarpments [4].

Figure 2.5 shows the separation zone (split of air flow where vortices or eddies are formed) over hill crests below which the wind speed may be reduced in a neutral atmosphere, without thermal effects. The regular wind profile is broken up at the separation zone and may be re-established further down on the leeward side.

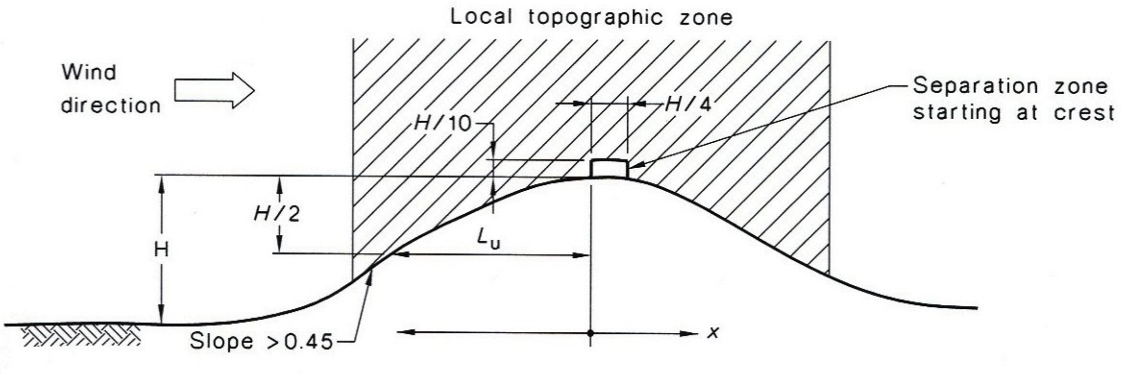


Figure 2.5 The separation zone over hill crests [4].

Observations of high wind damage during tropical cyclones in Northern Queensland indicate that speed-up effects can also occur during high winds on the upper slopes and crests of coastal mountain range escarpments. Analysis of damage patterns suggest a speed-up of 20% can occur frequently. The upper level of amplification of this speed-up is dependent on the escarpment slope profile, height and basic wind velocity. The AS/NZS 1170.2 Wind Actions [4] provides for values of up to 50%.

Overhead lines traversing an escarpment need to be carefully evaluated and have structures positioned to avoid, as far as possible, these potential extreme gust zones immediately below the escarpment edge, and in the zone immediately behind the crest.

2.4 Turbulence generation behind steep hills

In complex terrain it is often experienced that wind speeds on the leeward side of a steep mountain or hill may be significantly higher than they are on the windward side. This is mainly due to dynamic effects and may occur

1) on the leeward side of a rounded mountain ridge perpendicular to the wind (mountain waves),
2) behind singular hills with steep slopes on the leeward side.

Item 1) is an aerodynamic phenomenon, occurring in stable stratification of the lower atmosphere where the mean wind speeds may be enhanced. The involved phenomena are often on a larger scale and may be observed through the regular meteorological network, for instance in the form of mountain waves. They are described in many scientific reports, see for example [7] for an overview and more references. Typical areas for such phenomena are within and on the downwind side of mountain areas like the Rocky Mountains, White Mountains, Andes, the Greenland massif, the Alps, Ural and Himalayas. Stable stratification (inversions) may occur also in the free atmosphere and cause mountain waves which do not reach the ground.

Wave formations of smaller scales occur likewise in mountainous regions for example in Japan, the British Isles, Norway, New Zealand, Iceland, Germany, France and Canada. This may cause enhanced gust winds on the downwind sides at the wave troughs, see for instance [7] and [22]. A temperature inversion is required at the top of the mountain range for this phenomenon to occur.

The occurrence of the second phenomenon 2) is a combination of aerodynamic and mechanical effects and is not as well known as the first. This is mainly because of the more limited extensions of each hill, and the possible lack of recent reported wind damage. However, the most important reason may be the limited dissemination of general knowledge from the meteorological to the engineering scientific environments. Effects of this kind are generally known as “rotors” and “vortex streets”.

Figures 2.6 and 2.7 show two well-known historical examples of such topographical induced wind effects, taken from the Rock of Gibraltar [8] and Ailsa Craig, an island in the Firth of Clyde, west of Scotland. [9].

Figure 2.6 shows an example of a leeward screw-formed stationary rotor and turbulence generation from the Rock of Gibraltar with a large-scale wind from 220°. The upstream wind from southwest also flows around the tip of the Rock into its lee.

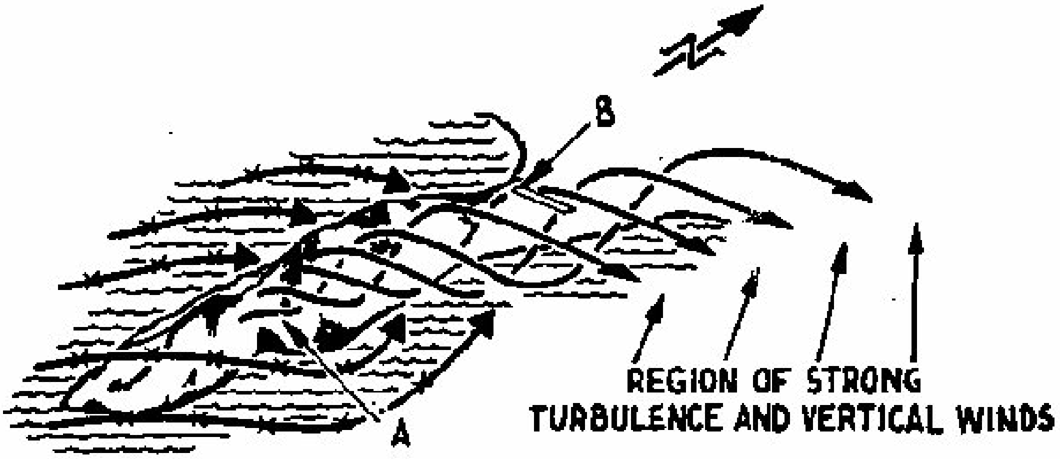


Figure 2.6 A leeward screw-formed rotor from the Rock of Gibraltar [8]

The point “A” shows the approximate location where metal shingles from a water supply tank have been sucked up by the vortex. “B” is the runway where the air traffic has flight track restrictions due to the strong side wind and turbulence that may occur in such situations.

Figure 2.7 is an example of a vortex street (also screw-formed) from Ailsa Craig. The marine traffic in the sea on the Eastern side of this island frequently experienced peculiar wind conditions. To investigate this, an aircraft dropped boxes into the air in winds from northwest (left side) and southwest (right side). In this situation it was shown that the incoming winds were inclined with respect to the long axis of the island, and a screw-formed vortex “street” was formed downwind. Winds from the West, which is perpendicular to the axis of the island, gave only simple flow separation (lower part).

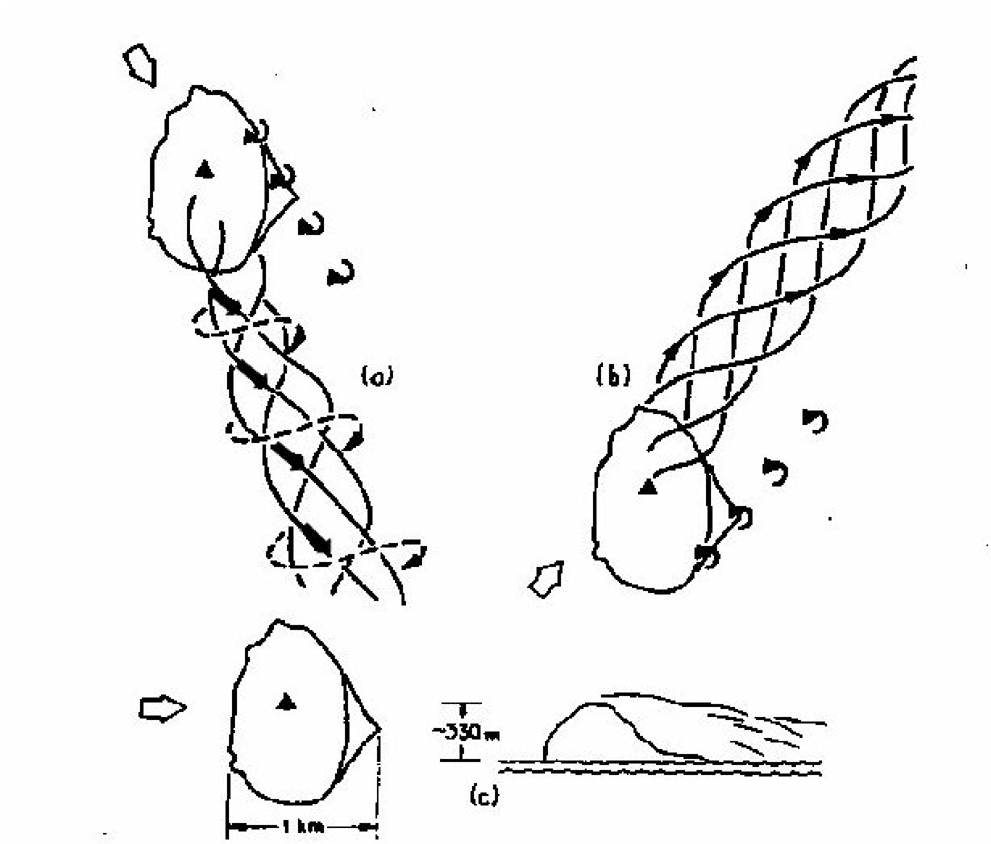


Figure 2.7 A screw-formed vortex street around Ailsa Craig adapted from [9].

The presence and danger of rotor wind development effects within close proximity of razor edge mountain ridges is well documented in aviation safety procedures. These are normally present at a height significantly above that of a normal overhead line structure. There are however, recorded instances where this effect is refracted and projected some distance downwind to impact within the ground level boundary layer zone. Evidence from New Zealand suggests this form of turbulence was the primary cause of lattice tower structure failures some 11 km downwind of a 2400 m high mountain ridge [20].

2.5 Speed-up effects over hills and ridges

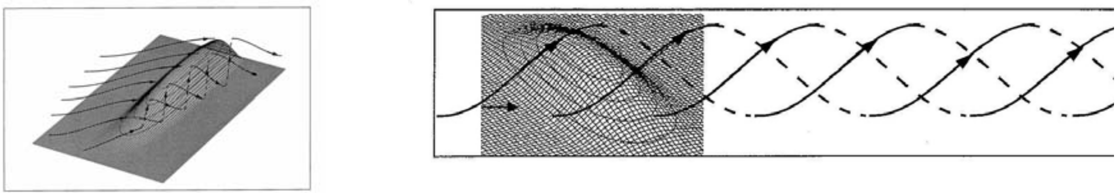


Figure 2.8. CFD examples of generation of a rotor on the leeward side of a 3-dimensional mountain ridge (left) and behind an isolated 3-dimensional hill (right). From [13].

Due to the Bernoulli effect (higher wind speed over the top of the ridge) the internal air pressure gets lower and hence air is sucked up along the leeward hillside. The two examples shown in Figure 2.8 are numerical computational fluid dynamics (CFD) modelling similar examples as in Figure 2.6 and 2.7.

Holmes [16], Letchford [17], Selvam and Holmes [18], have examined the speed-up effect that occurs over hills and ridges. This speed-up is usually referred to as a topographical multiplier M_t, which is the ratio of speed at a height over the feature to the speed at the same height in flat terrain. Holmes [16] investigated a single hill of slope 0.25 and found that the speed-up on the crest was a maximum of 1.2 near ground and decreased linearly to an effective height of 100 m above the crest of the hill.

Letchford [17] found similar results with a slight increase for the steeper ridges on embankments from 0.2 to 0.6. This later work resulted in a recommendation, in the absence of further data for New Zealand, to adopt a value of "$M_t = 1 + \text{slope}$" to be adopted and be applied at a height of 10m above the ridge where the slope exceeds 0.10.

Similar experiences are well known in many countries with hills and mountains. Some examples from Norway are given in [10, 11, 12 and 13], unfortunately only [12] is in English.

3 Wind gust and turbulence behind steep hillsides.

3.1 General

This chapter describes a procedure to identify some important topographic features creating severe vortex shedding and how to quantify the effect of such wind gust enhancements. The procedure follows the Norwegian Code for wind design published in 2002 [14]. This procedure is linked to general wind concepts in standard codes, although there is no other wind code, including IEC 60826 [2] that treats this type of turbulence generation.

3.2 Wind gust speed pressure and turbulence intensity

Some wind codes are based on the 10 minute averages of wind speed valid for the construction site, here called the "site specific wind speed" $v_s(z)$, where z is the height above ground.

The procedure below is in conformity with EUROCODE 1 – Wind (EN 1991-1-4) [21].

The peak value of the wind speed pressure, $q_{gust}(z)$ resulting from the gust wind speed is then found from:

$$q_{gust}(z) = 0{,}5\rho \cdot \mathrm{v}_\mathrm{s}^2\left[1 + 2k_\mathrm{p} I_\mathrm{v}(z)\right] = \left[1 + 2k_\mathrm{p} I_\mathrm{v}(z)\right] \cdot q_\mathrm{s}(z) \tag{3.1}$$

where
- ρ is the density of air
- $I_\mathrm{v}(z)$ is the turbulence intensity given by equation 3.2
- k_p is a peak factor usually set to 3.5, but it can vary between 3 and 4 depending on the structure.
- $q_\mathrm{s}(z)$ is the wind average pressure corresponding to v_s.

The turbulence intensity $I_\mathrm{v}(z)$, in the direction of the wind, is the ratio between the standard deviation $\sigma_\mathrm{v}(z)$ for the instantaneous wind (measured over 1s) and the corresponding 10-minute mean wind $\mathrm{v}_\mathrm{s}(z)$:

$$I_v(z) = \begin{cases} \dfrac{\sigma_\mathrm{v}(z)}{\mathrm{v}_\mathrm{s}(z)} = \dfrac{c_\mathrm{tt}}{c_\mathrm{t}} \cdot \dfrac{1}{\ln(z/z_0)} = \dfrac{c_\mathrm{tt} \cdot \mathrm{k}_T}{c_\mathrm{r}(\mathrm{z}) \cdot c_\mathrm{t}}; & for\, z \geq z_{\min} \\ I_\mathrm{v}(z_{\min}); & for\, z < z_{\min} \end{cases} \tag{3.2}$$

where:

z_0 is the roughness length of the terrain,
z_{min} is the starting level of the logarithmic wind profile, and
$c_r(z)$ and k_T are the terrain roughness factors given by the standards. IEC 60826 [2] has a classification of terrain categories reproduced here as Table 3.1. The values of roughness length z_0 and starting level for the logarithmic wind profile, z_{min}, are taken from [14].

Table 3.1 – Classification of terrain categories

Terrain category	Roughness characteristics	Z_0 (m)	Z_{min} (m)	K_R
I	Large stretch of water upwind, flat coastal areas	0.01	2	1,08
II	Open country with very few obstacles, for example airports or cultivated fields with few trees or buildings	0.05	4	1,00
III	Terrain with numerous small obstacles of low height (hedges, trees and buildings)	0.3	8	0,85
IV	Suburban areas or terrain with many tall trees	1	16	0,67

In Table 3.1, the roughness factor K_R represents a multiplier of the reference wind speed for conversion from one terrain category to another. According to IEC 60826 [2], for a line that follows the ridge of a hill, a terrain roughness which is smoother by one category than the one chosen for the area should be selected in order to be conservative. For a line running along a valley, the category III roughness should be chosen for all cases, whatever the terrain characteristics may be.

The roughness factor $c_r(z)$is defined as:

$$\mathrm{c_r(z)} = \begin{cases} k_T \ln(z/z_0) & \text{for } z_{min} \le z \le 200\,\mathrm{m} \\ c_r(z_{min}) & \text{for } z < z_{min} \end{cases} \tag{3.3}$$

The parameters c_t and c_{tt} are introduced in order to quantify the effects of local wind enhancements due to vortex shedding. The parameter c_t governs the changes in local wind speed because the air flows over hills, escarpments or mountains, and c_{tt} governs, together with c_t, also a possible increase in turbulence on the downwind side. The procedure to determine these parameters is given in the following section.

Note: In Europe the term “gust wind speed” is frequently referred to as average wind speed over 3-5s. Measured gust wind speeds are seldom defined specifically, but are mostly depending on the inertia (or response time for abrupt changes in wind speeds) of the anemometers in use.

3.3 Wake turbulence from significant topographical features, and the factors c_t and c_{tt}

3.3.1 Definition of the hillside

In order to determine the wind speed along an electric overhead line, it is necessary to use point values that may significantly influence the wind speed at a certain construction site (tower or span) along the line on the leeward side of a steep hillside. Such a hill is schematically shown in Figure 3.1.

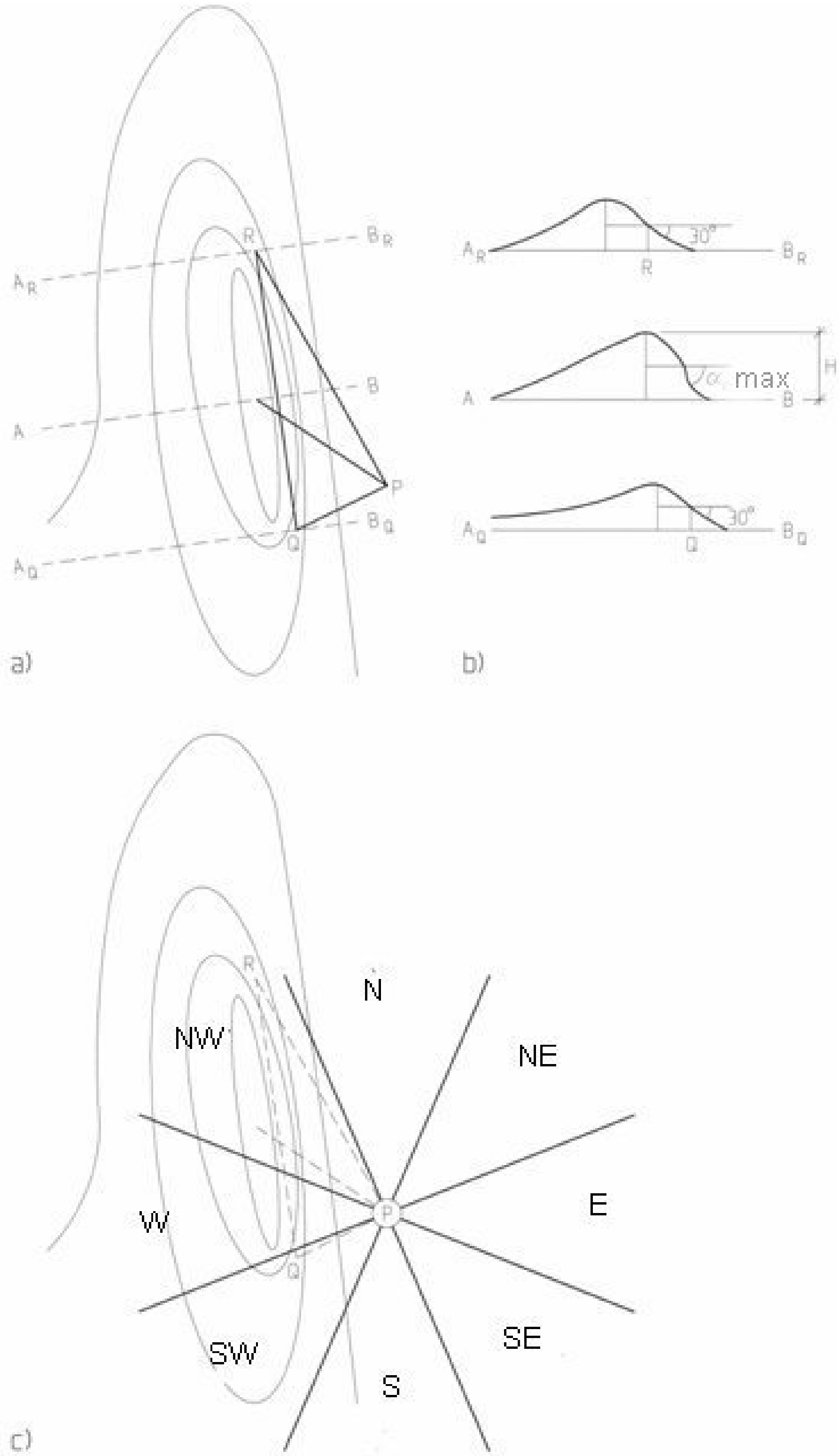


Figure 3.1 Example of steep terrain with possible wind gust enhancement at the point P. a) Map, b) Vertical cross section, and c) Map with directional sectors.

In order to establish the peak value for wind gust speed and the corresponding wind pressure q_{gust} on the leeward side of steep terrain, the symbols in Table 3.2 are used.

Table 3.2 Definition of parameters used

Parameter	*Definition*
P	Construction site
θ	Main wind direction, or sector of 45° centred along N, NE, E, SE, S, SW, W or W.
c_t and c_{tt}	Factors depending on topography (see Table A.2 in Appendix A).
L	Horizontal distance from P to top of mountain.
H	Height difference from P to top of mountain.
$\alpha_{max}(\theta)$	A declination angle representing the steep slope where potential turbulence may be formed. This declination angle is measured over an area with vertical height 0.5H and horizontal length about 2H.
$Q(\theta)$ and $R(\theta)$	Limit points in both ends of the steep terrain defined such as where the slope is getting below 30°. If the steep terrain extends across more than one sector θ, $Q(\theta)$ and/or $R(\theta)$ is/are chosen on the sector limit line.
$\angle PQR(\theta)$ and $\angle PRQ(\theta)$	Angles in the horizontal plane, within the sector θ, defined by the points P, Q and R
$I_v(\theta,z)$	Turbulence intensity within the sector θ at the height z above the terrain at point P.

Note: In complicated terrain it can be difficult to decide L, H, α and especially the points Q and R. As a general rule there shall be (near) free sight to the steep parts of the terrain generating the wind gusts. Near the end of a mountain ridge the selection of Q and R should be conservative. When in doubt on the decision of α_{max}, the highest parts of the steep slope should be emphasized.

3.3.2 Application of the parameters introduced

In Figure 3-1 a) and b) an example is shown of a terrain with a steep side, QR, along a ridge. This is outlined with contour lines and locations relative to the construction point P. Across the mountain ridge a cross section AB (perpendicular to axis of mountain) is shown where the maximum declination angle $\alpha_{max}(\theta)$ occurs within the sector θ. The cross sections A_RB_R and A_QB_Q, are defined to be located where the declination angle of the terrain is reduced to an angle of 30°.

Note: In Figures 3-1 a) and c), the sector of the steep slope QR seen from the point P is greater than 45°. In practical applications this sector will therefore be split into two smaller sectors, each being less than 45°, ref. the sector diagram outlined in Figure 3-1 c).

In Figure 3-1 c) the directional sectors θ are illustrated as the 8 main directions of the wind (N, NE, E, SE, S, SW, W and NW). For the sector θ = W, the point R will move to the division between sectors W and NW, i.e. 292.5°. For the sector NW, the point Q will move to the division between the sectors W and NW, i.e. 292.5° and R will be where it is marked in the Figure 3-1 c).

3.3.3 Procedure for calculation of wind gust enhancement

A procedure for the calculation of wind gust enhancement is given in Appendix A, where the necessary questions are given. All answers to these questions are filled in a table provided. It is important to notice that it is very well possible to have a larger net enhancement from another sector than that with the highest reference wind speed. This is due to the combination of slope steepness and distance from the mountain base in each case.

3.3.4 Wind variations with height above ground

A roughness length of maximum 0.05 m is recommended in areas where the wind speed is enhanced by topography. Since the (upper) boundary conditions do not apply in such wind fields there are reasons to believe that even lower values for z_0 may be applied where the construction site is surrounded by high and steep mountains (alpine landscape). A study in Norway [15] indicated z_0 lower than 0.003 in a valley/fjord area in between mountains of 1000 m or more.

The distribution of wind velocity with height is known to be significantly different in narrow windstorms such as severe thunderstorms than in fully developed gales or cyclones. Physical and numerical modelling of thunderstorm downdrafts by Holmes [16], Letchford [17], Selvam and Holmes [18], have shown that there is a maximum wind speed developed between 0.3 and 0.6 δ above ground, where δ is the height at which the velocity reaches half its maximum value. Above this height the velocity has been found to drop off markedly. These studies indicate that a structure approximating a 50 – 70 m tower will be fully loaded over its height if impacted by these high wind gusts.

This aspect should be considered individually when necessary.

3.3.5 Roughness change

Close to a roughness change limit (for example, the seashore or urban area outskirts) the distance covered by the wind on the “rough” terrain may be enough so that the braking effects of the ground are significant up to a certain height, but insufficient to affect the wind for greater heights above ground. Intuitively, the wind speed profile is determined by rough parameters more for small heights than for larger ones.

Different models have been proposed to describe this complex phenomenon, without any global agreement on recommended procedures. In the case of more extreme topography as discussed in this report, the complexity is even more pronounced, and the downstream influence of such topography must therefore be considered individually.

4 Other Local Effects

4.1 General

Some other topographical features and their influence on wind conditions are mentioned in general terms in this chapter.

4.2 Low Mountain Ranges Channelling Effects

Where wind storms have the potential to track within frontal weather systems over relatively flat to undulating land, they normally travel in a predominant direction. Thunderstorm winds generated from such systems occur as outflow winds or as isolated wind phenomena such as downbursts or severe downdrafts, are normally characterised by narrow damage paths with widths up to 2000 m at ground level.

When these high intensity wind gusts with velocities ranging from 30 – 60m/s approach local mountains, the wind flow patterns are significantly modified and can be channelled and redirected.

Structures placed within predominant features, such as gaps between mountain ridges, in narrow river valleys through mountainous zones, and on low ridges within higher mountain zones can be severely affected.

Velocity speed-up, local turbulence and wind eddies can have complex effects on structure wind loadings. Evidence from transmission line tower failures within a narrow valley between 500m high mountain ridges in Queensland during a severe thunderstorm downburst, has indicated speed-up effects of 30% compared with 10m reference wind velocities. As these downbursts impacted on the 54m high structures, there was also evidence of possible high turbulent effects 30m high above the valley floor

4.3 Valley Channeling /Funneling Effects

High intensity wind flows along valleys provide directional control of wind flow patterns. Where there is a narrowing of these valleys, such as towards and at the valley head, there is the potential for wind speed-up effects to occur. Studies for wind turbine sites indicate wind speeds can increase typically by up to 20% at a height above the crest of 0.1 x escarpment height above the valley floor.

4.4 Converging Mountain Ridge Effect

In a similar way to the channelling effects of valleys, converging mountain ranges and passes have a similar effect on wind velocities. Structure siting within narrow passes needs to be carefully considered.

4.5 Katabatic Wind Effects

In many high mountainous regions, downdrafts of cold air from high plateaus, ice and snow regions, and from high altitude air flows as a result of large scale temperature inversion or draw down effects from weather systems, can occur. These are sometimes more pronounced in some falling valleys from these mountainous regions and wind velocities up to 60 m/s have been recorded. These valley areas are, in most cases, denuded of vegetation and have normally never been used for residential purposes. Where vegetation has survived over time, evidence exists of wind impacts on plant growth. As a general rule, this type of wind occurs for long periods with the potential to significantly damage any structure placed within its path.

4.6 Extensive Fetch Distances

Transmission line structure placement often needs to occur on elevated positions where the line route passes over low ranges or around other topographical features. Such positions are more exposed to any approaching significant wind storm and in most cases the terrain will be Category 1 even though the local terrain could be Category 4 [2].

5 Application of numerical weather forecasting models

In complex terrain is also possible to perform particular studies of wind flow based on local scale numerical weather forecasting models [BOOK & IVAR]. Figure 5.1 shows an example from a village frequently exposed to strong wind gusts. The village is situated in the bottom of a fjord, towards NW, and two valleys, towards S and SE. The mountains around the fjord and the two valleys range up to more than 1 500 m asl. Strong winds from the sector E - S generate regularly extreme wind gusts within the village area.

In connection with the planning of a transmission line crossing the village perpendicular to the axis of the fjord, the design wind gust speeds at a tower height of 60 m was calculated to 75 m/s by using the standard wind code applied on local measurements.

Figure 5.1a. A topographical map around a village (red dot) where surrounding mountains range up to more than 1 500 m asl. (North: upwards in Figs a. and b.

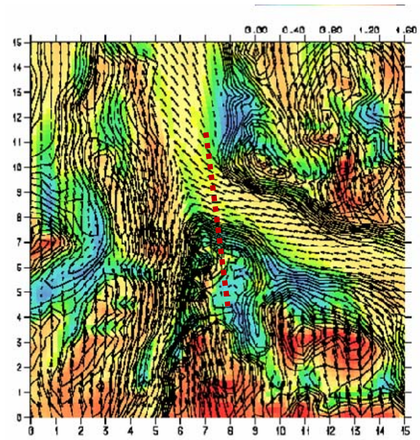


Figure 5.1b Numerical simulations of a strong wind situation in the same area as in a. Arrows show wind directions and wind speeds. Speeds are also represented by colours (red: high, yellow medium and blue low). Size of map: 15km x 15 km.

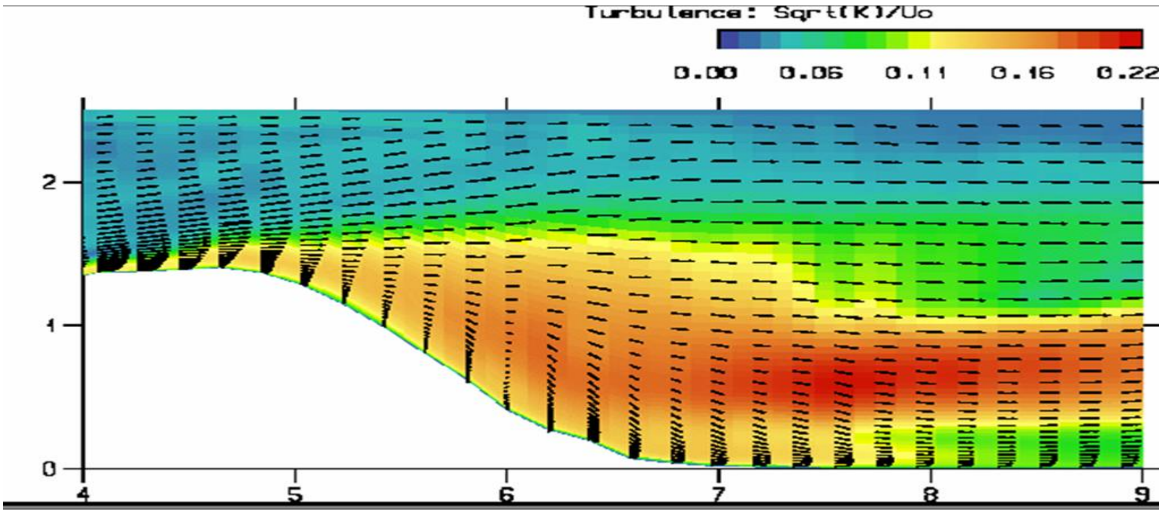


Figure 5.2. Cross section along the red dotted line in Figure 5.1b from south (left) to north (right). Vertical columns of arrows show Wind speeds and directions (in the plane of the figure). Colours show turbulence intensities (scale on top).

A numerical study was performed by using a local scale weather forecasting model in parallel with measurements of wind speeds and directions up to 50 m above ground, see Figures 5.1a-b. During the high wind conditions that occurred during the period the model results were in extremely good agreement with the measured values. Moreover, it was found that the vertical wind profiles recommended in regular wind Codes did not apply. The “terrain roughness” in this case was comparable with that over “open water” at the building site (position 7 km in Figure 5.2).

The main reason for the near constant wind speed with height (up to about 1 000 m in this case) is that it develops a separate “boundary layer” within valleys below high mountains. The general theory behind general wind profiles do therefore not apply in such topography, as this theory assumes a wide (infinite) area of homogenous roughness. This is obviously not the case below the average level of the mountain tops here. However, it is also shown in Figure 5.2 that very high turbulence intensities dominate between 400 m an 1 000 m above ground.

By this approach the design wind speed could be reduced to 60 m/s at the top of the transmission line towers.

From this study it can be concluded that wind conditions in general and especially wind profiles, may preferably be studied by using numerical atmospheric models in very complex mountain topography.

6 Summary

Standard codes for wind engineering and design of structures include general rules for speed-up of winds over hills and escarpments and will provide the general wind engineering requirements for design of electrical overhead power lines. There are however limitations for the application of these general rules for treating extreme terrain roughness, predominant hill forms and escarpments, such as many high hills, mountains, valleys and fjords. This brochure provides guidelines for the better evaluation of the potential high wind velocities as they are affected by predominant terrain features. It demonstrates a procedure to be followed in order to identify areas where gust wind speeds may be enhanced particularly due to steep mountain slopes and edges and includes application examples. Some of the methodology described in this document was developed in connection with a revision of the recent Norwegian Building Code, NS3491-4 (wind loads) (2002) [14]. In complex terrain it is often experienced that wind speeds on the leeward side of a steep mountain or hill may be significantly higher than they are on the windward side. This is mainly due to dynamic effects and may occur

1) on the leeward side of a rounded mountain ridge perpendicular to the wind (mountain waves),
2) behind singular hills with steep slopes on the leeward side.

Item 1) is an aerodynamic phenomenon, occurring in stable stratification of the lower atmosphere where the mean wind speeds may be enhanced. Typical areas for such phenomena are within and on the downwind side of mountain areas like the Rocky Mountains, White Mountains, Andes, the Greenland massif, the Alps, Ural and Himalayas.

The occurrence of the second phenomenon 2) is a combination of aerodynamic and mechanical effects and is not as well known as the first. This is mainly because of the more limited extensions of each hill, and the possible lack of recent reported wind damage.

A procedure is given to identify and evaluate the parameters necessary to quantify the effects of local wind enhancements due to vortex shedding. In order to determine the wind speed along an electric overhead line, it is necessary to use point values that may significantly influence the wind speed at a certain construction site (tower or span) along the line on the leeward side of a steep hillside.

An application example is shown in Appendix B for a 132 kV electric overhead line which runs parallel with, and on the leeward side of a steep mountain range with heights up to 600 m above the level of the line.

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Appendix A – Procedure for calculation of wind gust enhancement

Values for c_t and c_{tt} for the construction site P are determined with the help of Table A.1 and Figures 3-1 and A.1. A map of scale 1:50 000 is useful for this procedure. A transparency with a print of the eight sectors (ref. Figure 3.1c)) may be used as a template for the sector analyses.

The procedure is shown schematically in Table A.1 where the necessary questions are given. All answers to these questions are filled in columns 3 – 10. The answers for rows 3 and 4 shall be either "Yes/value" or "No". For row 5 the answer shall be "Area number" or the sign " – " where the category is not defined. For the other rows the answers shall be given as the value of the actual parameter, or with the sign " – " where the value is not relevant.

Table A.1 can be filled in stepwise as recommended below:

1. Fill in answers in columns 3 – 10 for each of the rows 1 – 3.
2. Check row 3 for "No" in any of the columns 3 – 10. If this is the case, this is a sector without wind gust enhancement and the value 1.0 is noted in row 7 for this (these) column(s) and " – " in all other remaining row(s) of that column.
3. Proceed with relevant answers in row 4 for all possible remaining columns with "yes" in row 3.
4. Check row 4 for "No" in any of the columns 3-10. Where this is the case, this is a sector without wind gust enhancement and the value 1,0 is inserted in row 7 in this column and "-" in all remaining rows in the same column.
5. The procedure is concluded by determining the parameters in rows 5-7 for each of the columns 3-10 that does not contain the sign "-".

Table A.1 Procedure scheme for the determination of c_t and c_{tt} on the leeward side of the steep terrain.

Row number	Question	θ=N	θ=NE	θ=E	θ=SE	θ=S	θ=SW	θ=W	θ=NW
1	L= ? 1)								
2	H= ? 1)								
3	Is L<15H ?								
4	Is α_{max}>30° ? 1)								
5	Area number = ? 2)								
6	c_t= ? 3)								
7	c_{tt}= ? 3)								

1) To be decided from a map (Figure 3.1) and Table 3.2.

2) To be decided from Figure A.1

3) To be decided from Table A.2

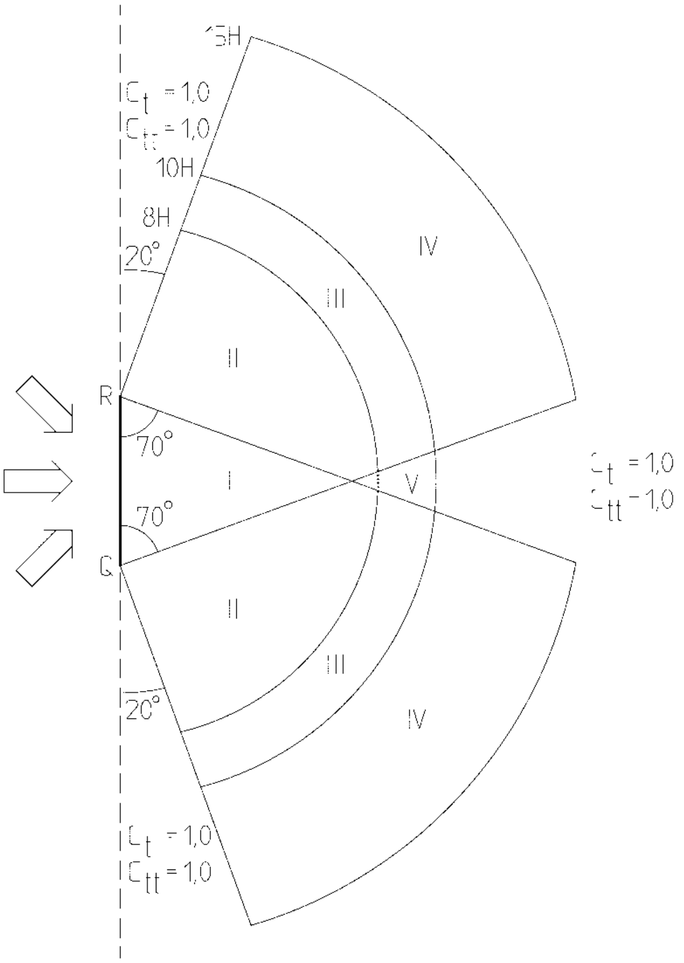

Figure A.1 Area numbers I - V for wind gust enhancements in point P, ref Figure 3.1, on the leeward side of a steep terrain, ref Table 3.1. The points Q and R are the same as in Figure 3-1.

For an elongated ridge or an escarpment with alternating steep and less steep parts, this shall be considered as a continuous steep terrain even if $\alpha_{\max} < 30^\circ$ at some places.

Table A.2 Coefficients c_t and c_{tt} on the leeward side of a steep terrain based on the area numbers α_{max}(θ and L.

α_{max}:	$30^{o} < \alpha_{max}(\theta) \leq 40^{o}$		$\alpha_{max}(\theta) > 40^{o}$		
L:	L ≤ 8H		L ≤ 10H		10H < L ≤ 15H
Area number 1)	I or V	II	I, II or III	V	IV
c_t:	1,0	0,9	1,0	0,9	0,9
c_{tt}:	1,0	1,75	1,75	1,75	1,75

1) The area number of point P is decided in Figure A.1.

From Figure A.1 and Table A.2 it is seen that gust enhancements only occur when the wind direction is somewhat inclined with respect to the axis of the mountain. When the wind is perpendicular to this axis almost no gust enhancements are found, see also measurements from Ailsa Craig in Figure 2.7.

It is important to notice that it is very well possible to have a larger net enhancement from another sector than that with the highest reference wind speed. This is due to the combination of slope steepness and distance from the mountain base in each case.

Appendix B – Application example for wake turbulence

Practical Example

Figure B.1 shows the right-of-way of a new 132 kV line from a planned wind farm on an island in Northern Norway. This island is known to have very extreme wind conditions, in particular behind the steep and sharp mountains on the island. The map shows that there are two areas with such rugged mountains, one in the northern part and another and bigger in the southern part. In between them there is a plain area where the line is fully open to the Norwegian Sea towards west (left in the map).

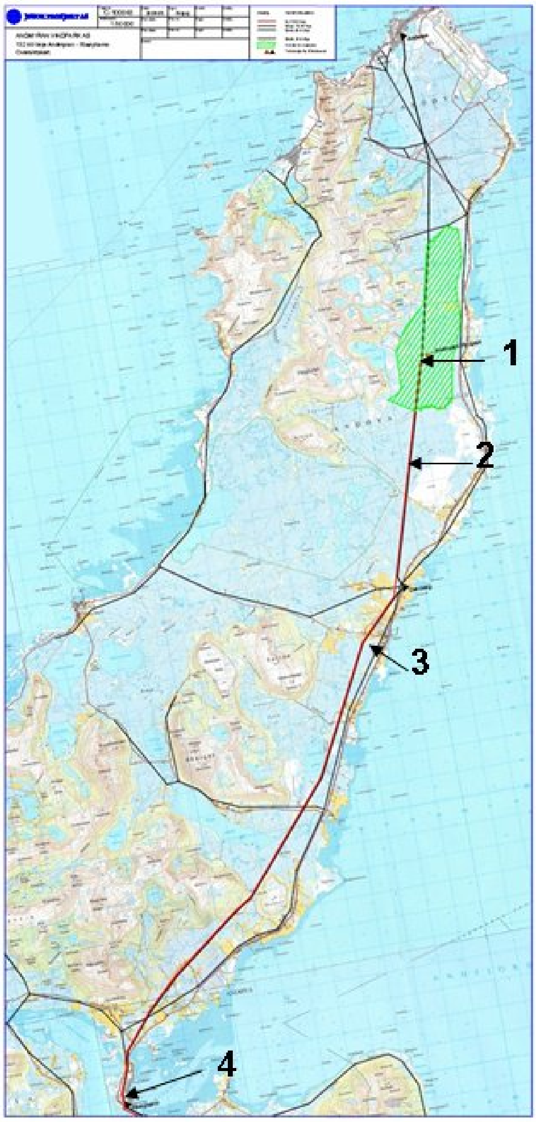

Figure B.1. Right-of-way for a new 132 kV line (red line) from a planned wind turbine park (green shadow) to a substation at Rishøyhamn (south end). The map is provided by the engineering company Jøsok Posjekt AS, Bergen, Norway.

The northern part consists of mountains mostly in the 200 – 300 m levels, but some peaks are up to the 400 m level and "Sverigetinden" reaches 522 m asl. The southern part consists of somewhat higher peaks. Several of them are above 600 m asl.

The distances between the steep mountain sides and the line are typically 1 – 4 km.

Wind gust enhancements relevant for exposed parts of the line

Terrain category. Enhancements of wind gusts will restrict the terrain roughness to type II according to Table 3.1. This means:

$k_T = 0{,}19$
$z_0 = 0{,}05$ m
$z_{min} = 4$ m

In this example it is necessary to look at the overall variability of wind gusts along the line sections instead of considering individual points of the sections. To obtain an overall picture, all area numbers given in Figure A.1 will be considered in the following. Values for c_t and c_{tt} in Table B.1, cover slopes between 30° and 40° as well as over 40°.

Area number. The mountain tops are up to 500 m above the line sections and the distance from the steep terrain to the line sections is typically 1- 2 km, or less than 4 times the height difference. Hence the relevant area numbers are I and II (Figure A1) for these sections. For the sake of completeness, all area numbers are considered below.

Turbulence intensity. In order to calculate the wind gust speed pressure (chapter 4), or gust wind speeds, it is necessary to obtain the turbulence intensity estimates for the area. By inserting the values for c_t and c_{tt} in the upper middle term for I_v in equation (3.2) the turbulence intensities for the selected heights are obtained and given in Table B.1 for 10, 20 and 30 m above ground.

Gust wind speeds. If instead of gust wind pressures, wind gust speeds are required, these can be obtained using the gust factor k_{gust}, from equation. (B.1):

$$k_{gust} = \sqrt{1 + 2k_p \, I_v(z)} \tag{B.1}$$

Applying the values of I_v for z = 10 m and $k_p = 3{,}5$ (as for EN 1991-1-4) on $v_s(10) = 29$ m/s gust wind speeds can be estimated for each area number, as given in Table A.1, and applying factor k_{gust} on v_s gives $v_s(20) = 33$ m/s and $v_s(30) = 35$ m/s for 20 and 30 m above ground, respectively. Corresponding turbulence intensities and gust wind speeds are also given in Table B.1 for illustration.

Table B.1 Parameters for example calculations.

	$30 < \alpha \leq 40$		$40 \leq \alpha$		
Area number	I & V	II	I, II & III	V	IV
c_t	1,0	0,9	1,0	0,9	0,9
c_{tt}	1,0	1,75	1,75	1,75	1,75
$z = 10m$ & $v_s(10) = 29$ m/s :					
$I_v(10m)$	0,19	0,37	0,33	0,37	0,37
$k_{gust}(10m)$	1,53	1,89	1,82	1,89	1,89
$v_{gust}(10m)$	44 m/s	55 m/s	53 m/s	55 m/s	55 m/s
$z = 20m$ & $v_s(20) = 33$ m/s :					
$I_v(20m)$	0,17	0,32	0,29	0,32	0,32
$k_{gust}(20m)$	1,47	1,81	1,74	1,81	1,81
$v_{gust}(20m)$	49 m/s	60 m/s	57 m/s	60 m/s	60 m/s
$z = 30m$ & $v_s(30) = 35$ m/s :					
$I_v(30m)$	0,16	0,30	0,27	0,30	0,30
$k_{gust}(30m)$	1,45	1,77	1,71	1,77	1,77
$v_{gust}(30m)$	51 m/s	62 m/s	60 m/s	62 m/s	62 m/s