Eurocode 1: Action on structures

Part 1-4: General Actions
Wind Actions

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Calculation Procedure of Wind Actions

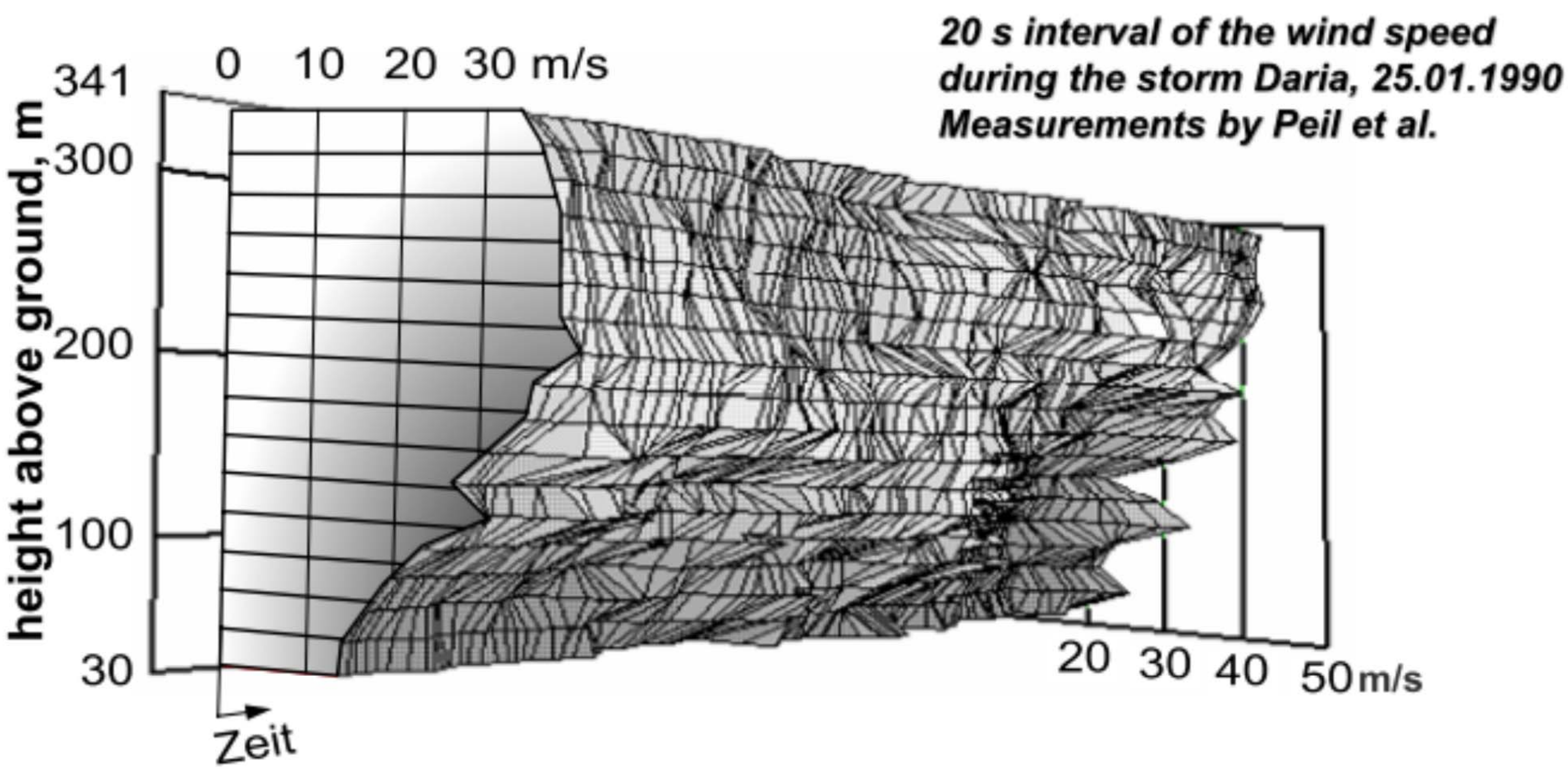
Overview

Parameter
Peak velocity pressure q_p
Wind pressures, e.g. for claddings, fixings and structural parts external pressure $w_e = c_{pe} \cdot q_p(z_e)$ internal pressure $w_i = c_{pi} \cdot q_p(z_i)$
Wind forces on structures, e.g. for overall wind effects $F_w = c_s c_d \cdot c_f \cdot q_p(z_e) \cdot A_{ref}$

Calculation Procedure of Wind Parameters

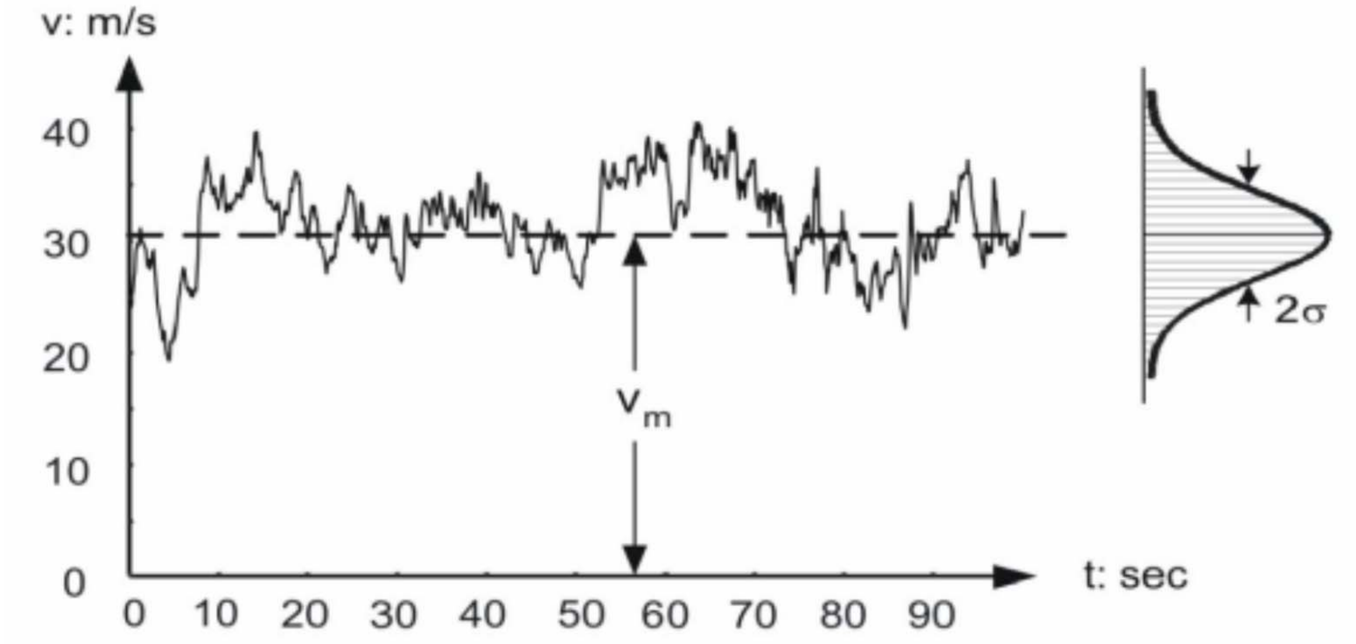
Parameter
peak velocity pressure q_p
basic wind velocity v_b
reference height z_e
terrain category
characteristic peak velocity pressure q_p
turbulence intensity I_v
mean wind velocity v_m
orography coefficient $c_o(z)$
roughness coefficient $c_r(z)$

Wind Speed and Turbulence



The atmospheric wind is a stochastic process, described by its statistical parameters:
point parameters: mean value, standard deviation, spectra ;
field parameters: correlations, cross-spectra.

Wind Speed and Turbulence

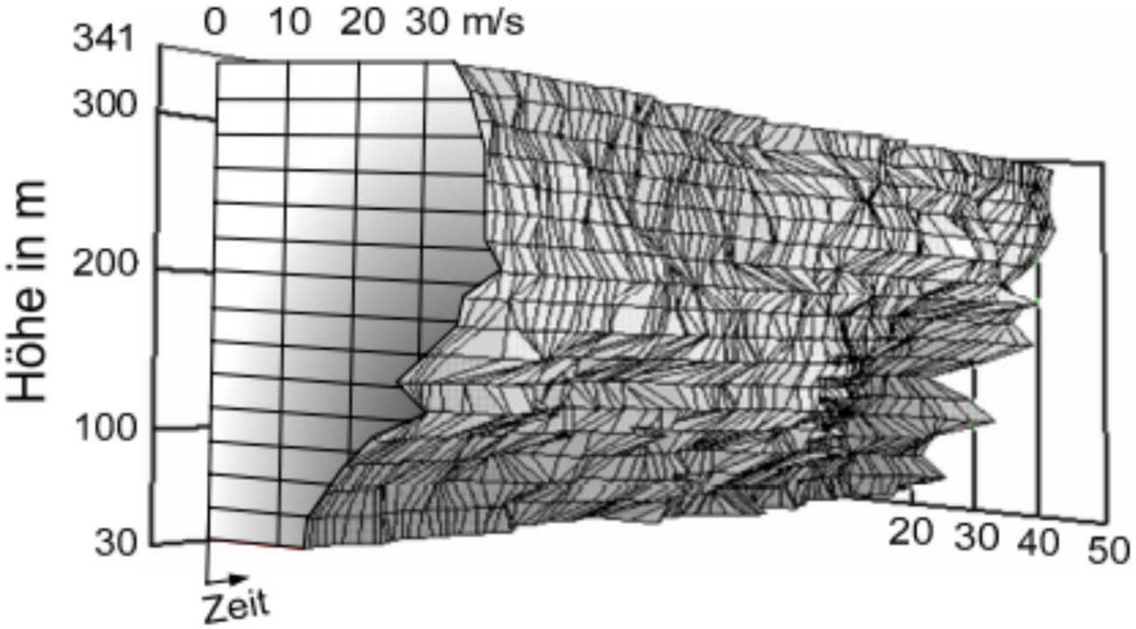


Time series of the wind velocity at a point

Statistical point parameters

v_m - the mean wind velocity;
σ_v - the standard deviation of velocity fluctuations due to wind turbulence;
I_v - the intensity of wind turbulence,
$I_v = \sigma_v / v_m$.

Peak Velocity Pressure: Definition



The peak velocity pressure includes the mean wind v_m and the short term velocity fluctuations due to wind turbulence.

$$q_p(z) = \left[1 + 7 \cdot I_v(z)\right] \cdot \tfrac{1}{2} \cdot \rho \cdot v_m^2(z)$$

ρ is the air density

$\tfrac{1}{2} \cdot \rho \cdot v_m^2(z)$ accounts for the mean wind and is its velocity pressure

$\left[1 + 7 \cdot I_v(z)\right]$ accounts for wind turbulence in the peak velocity pressure

Basic Wind Velocity v_b

$$v_b = c_{dir} \cdot c_{season} \cdot v_{b,0}$$

defined as a function of wind direction and time of year at 10 m above ground of terrain category II

$v_{b,0}$ is the fundamental value of the basic wind velocity, see (1)P

c_{dir} is the directional factor, see Note 2. The recommended value is 1,0.

c_{season} is the season factor, see Note 3. The recommended value is 1,0.

The fundamental value of the basic wind velocity, $v_{b,0}$

* is a mean speed averaged over 10 min;
* is calculated from the mode of the mean wind vector irrespective of wind direction.
* is measured at 10 m above ground level; generally in flat, open country corresponding to terrain category II with low vegetation; for mountainous regions, the National Annex may give special procedures

Basic Wind Velocity v_b

(continued)

The fundamental value of the basic wind velocity, $v_{b,0}$ is a characteristic value in terms of EN 1990: it is exceeded with a probability 0,02 in each year, in other words the return period is 50 years.
The fundamental values are given in the National Annex, typically in a wind map.

Basic Wind Velocity v_b for different exceedence probability

For temporary structures or for states during execution, a higher level p of exceedence probability may be acceptable. Then, the basic wind velocity may be adapted by multiplying the basic wind velocity v_b by the probability factor c_{prob}.

$$c_{prob} = \left(\frac{1 - K \cdot \ln(-\ln(1-p))}{1 - K \cdot \ln(-\ln(0{,}98))} \right)^n$$

K is the shape parameter

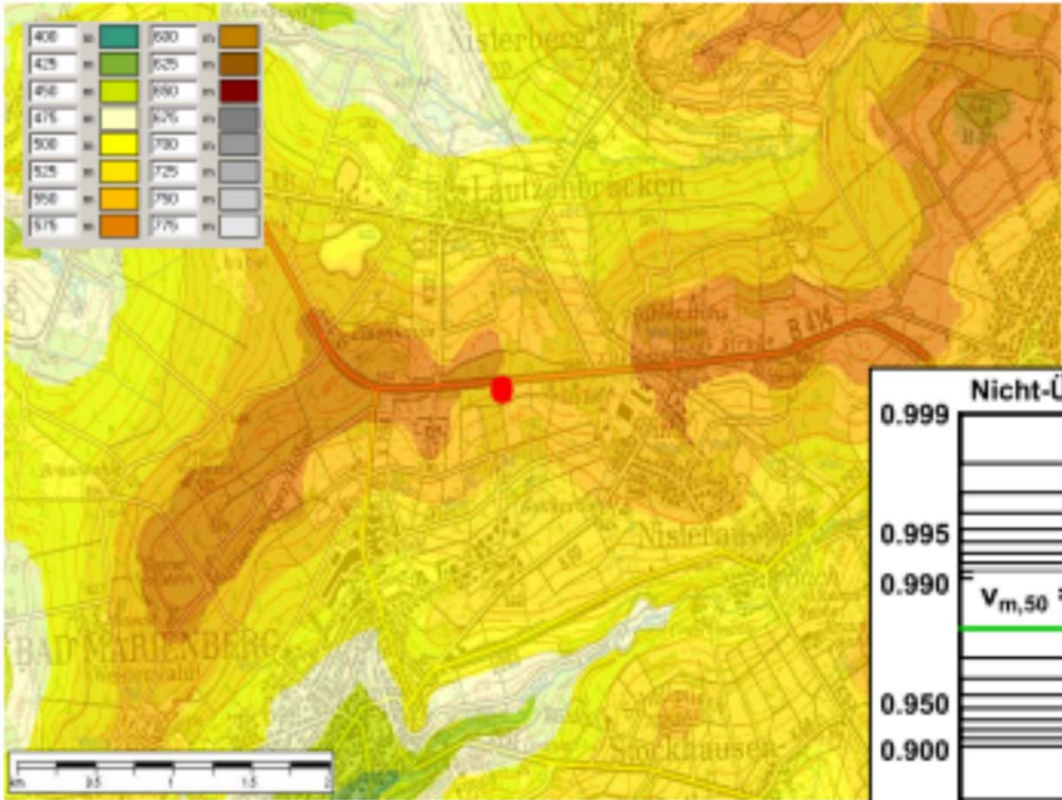
n is the exponent.

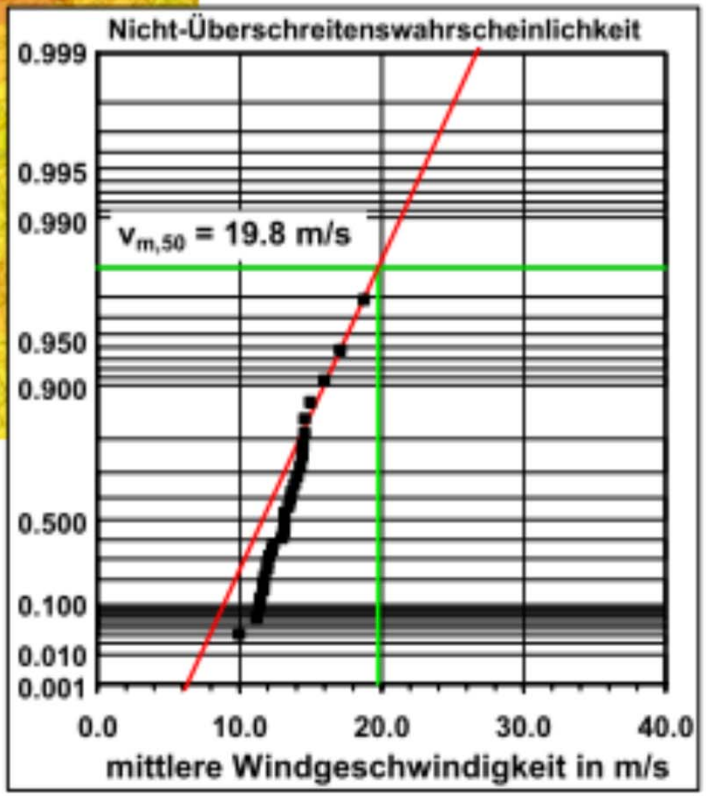
Typical parameter sets are:

$K = 0{,}2$; $n = 0{,}5$ (recommended)

$K = 0{,}1$; $n = 1{,}0$ (also plausible)

Fundamental Value of the Basic Wind Velocity $v_{b,0}$ from Wind Statistics

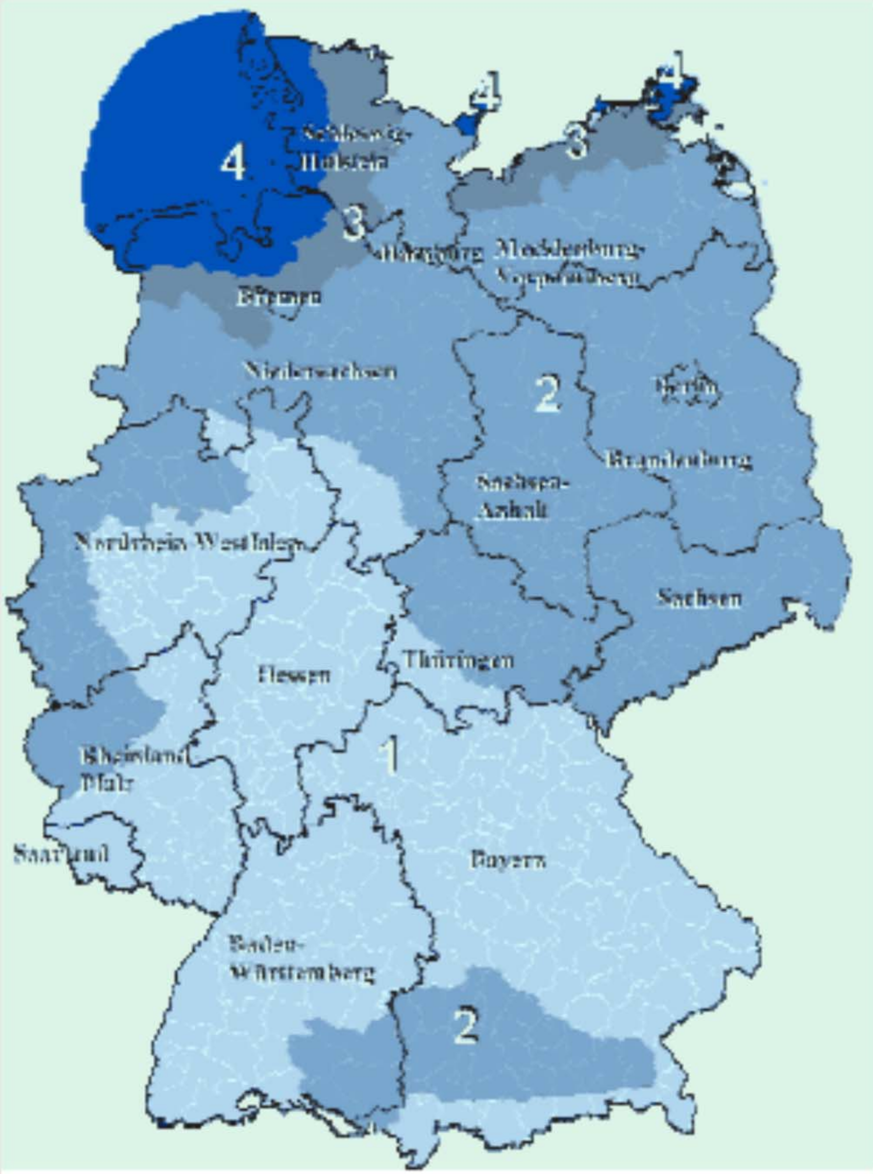




Bad Marienberg, Westerwald
547 m ü.N.N.
n = 31 Jahre

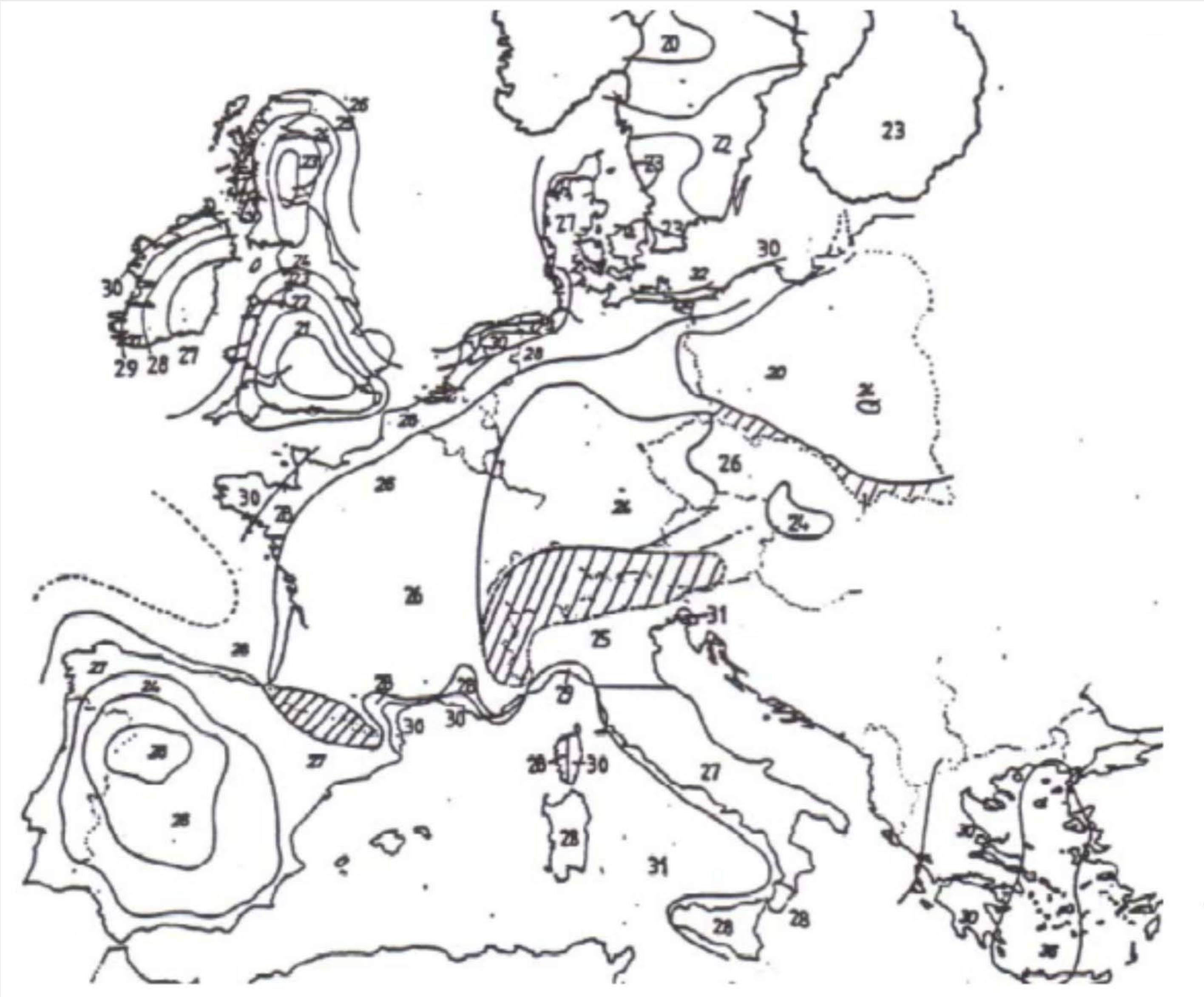
$v_{m,50}$ = 19,8 m/s

Wind Map of Germany



Windzone	$v_{b,0}$	$q_{b,0}$
WZ 1	22,5 m/s	0,32 kN/m²
WZ 2	25,0 m/s	0,39 kN/m²
WZ 3	27,5 m/s	0,47 kN/m²
WZ 4	30,0 m/s	0,56 kN/m²

Sketch of a European Wind Map of the Fundamental Value, $v_{b,0}$



Mean Wind Profile

$v_m(z) = c_r(z) \cdot c_o(z) \cdot v_b$ the mean velocity at height z above ground, the mean wind profile, depends on terrain roughness and orography

$c_o(z)$ is the orography factor, taken as 1,0 unless otherwise specified

$c_r(z)$ is the roughness factor,

$$c_r(z) = k_r \cdot \ln\left(\frac{z}{z_0}\right)$$

z_0 is the roughness length

k_r terrain factor depending on the roughness length z_0

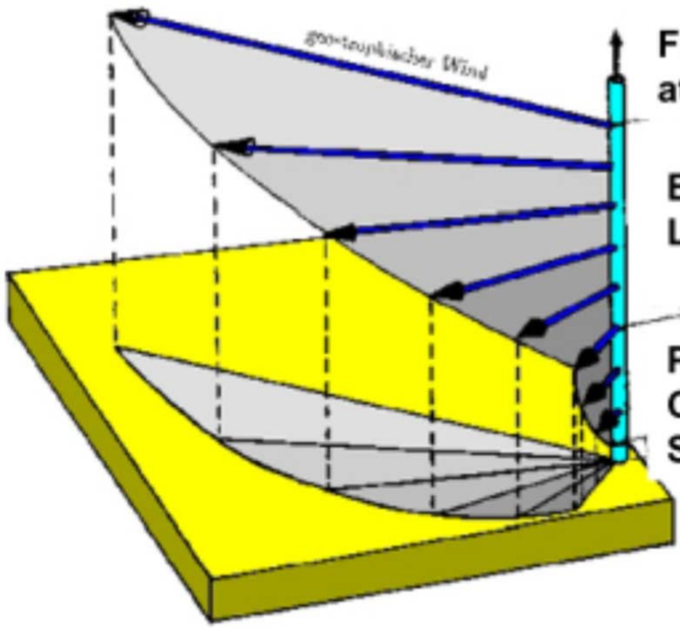
$$k_r = 0{,}19 \cdot \left(\frac{z_0}{z_{0,II}}\right)^{0{,}07}$$

$z_{0,II}$ = 0,05 m (terrain category II)

Background to Mean Wind Profiles

The ***free atmosphere*** begins at large heights above the earth's surface, at the ***gradient height*** δ. This height is in the order of several 1000 m.

The ***gradient wind*** speed is driven by the horizontal pressure gradient. The gradient wind is directed parallel to the isobars.



In the ***planetary boundary layer*** below the gradient height, the wind is retarded by surface friction. It decreases continuously to zero at the ground. The mean wind speed veers to the low pressure at angles of 20°-30° (**Ekman spiral**).

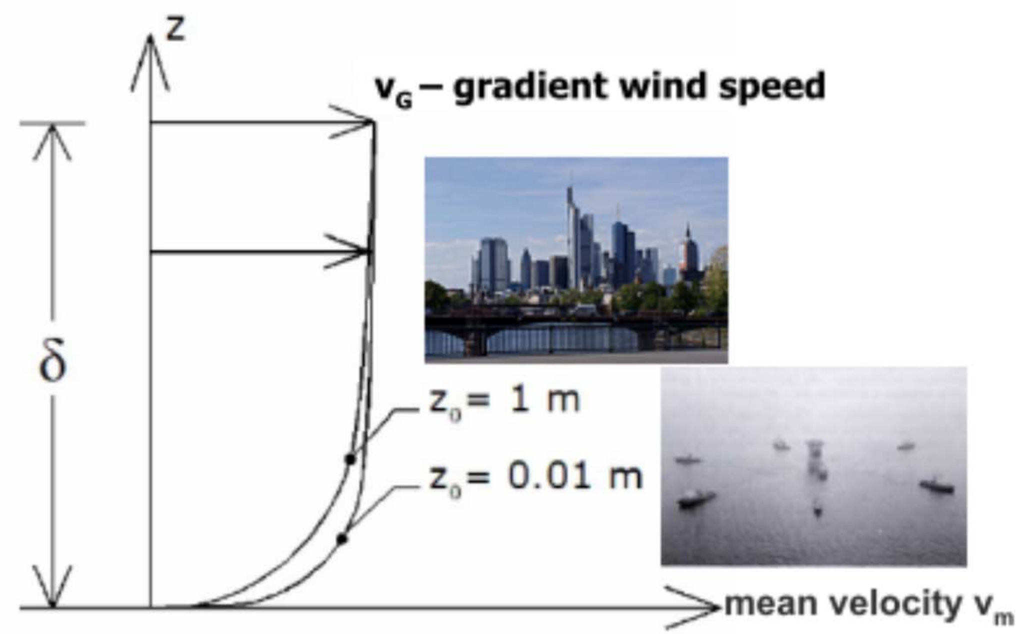
The surface friction generates ***flow fluctuations*** as a transfer of kinetic energy from the mean flow to flow turbulence.

The ***standard deviation*** of the flow fluctuations, the measure of turbulence, is constant in the Prandtl Layer. In the Ekman Layer, it decreases to zero at the gradient height δ.

Background to Mean Wind Profiles

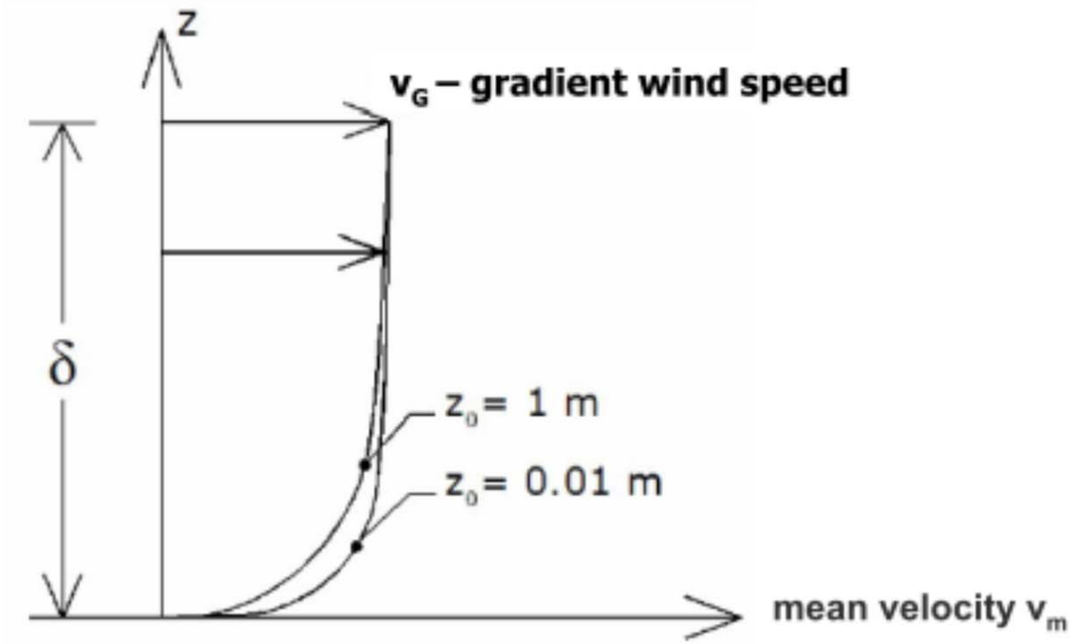
The mean wind profile depends on the roughness of the ground surface

The roughness length z_0 represents the intensity of wind shear between ground surface and wind flow



	roughness length	ABL-height
smooth, flat country, open sea	z_0 = 0.01m	δ = 2600 m
built-up urban area	z_0 = 1m	δ = 3600 m

Background to Mean Wind Profiles



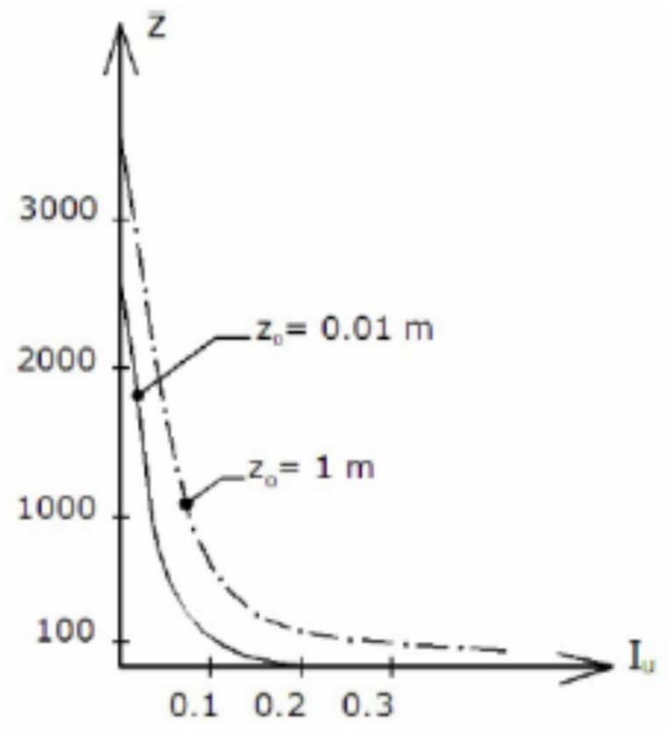
Close to the ground up to a height of ca. 100m, the mean wind profile of the planetary boundary layer may be approximated by a constant shear model.

For it, Ludwig Prandtl derived the logarithmic law of the flow profile:

$$v_m(z, z_0) = \frac{v_m(10, z_0)}{\ln \frac{10}{z_0}} \ln \frac{z}{z_0}$$

The log. law is applied in the Eurocode for heights less than 200m.

Background to Turbulence Intensity



$z_0 = 0.01\ m$

$z_0 = 1\ m$

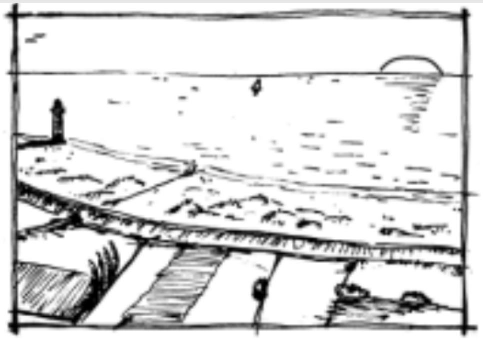
$$I_u(z,z_0) = \frac{1}{\ln\frac{z}{z_0}}\left(1-\frac{z}{\delta}\right)$$

Terrain categories and terrain parameters (1)

Terrain category 0

Sea, coastal area exposed to the open sea

roughness length $z_0 = 0{,}003$ m
minimum height $z_{min} = 1$ m
terrain factor $k_r = 0{,}156$
roughness factor at z = 10 m
$c_r(10) = 1{,}266$



Terrain category I

Lakes or area with negligible vegetation and without obstacles

roughness length $z_0 = 0{,}01$m
minimum height $z_{min} = 1$ m
terrain factor $k_r = 0{,}170$
roughness factor at z = 10 m
$c_r(10) = 1{,}173$

Terrain category II - **reference terrain**

Area with low vegetation such as grass and isolated obstacles (trees, buildings) with separations of at least 20 obstacle heights

roughness length $z_0 = 0{,}05$ m
minimum height $z_{min} = 2$ m
terrain factor $k_r = 0{,}190$
roughness factor at z = 10 m
$c_r(10) = 1$

Terrain categories and terrain parameters (2)

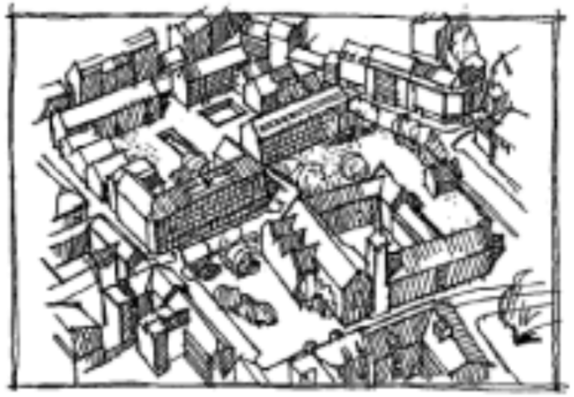
Terrain category III

Area with regular cover of vegetation or buildings or with isolated obstacles with separations of maximum 20 obstacle heights (such as villages, suburban terrain, permanent forest)

roughness length $z_0 = 0,3$ m
minimum height $z_{min} = 5$ m
terrain factor $k_r = 0,198$
roughness factor at z = 10 m
$c_r(10) = 0,694$

Terrain category IV

Area in which at least 15 % of the surface is covered with buildings and their average height exceeds 15 m



roughness length $z_0 = 1,0$ m
minimum height $z_{min} = 10$ m
terrain factor $k_r = 0,234$
roughness factor at z = 10 m
$c_r(10) = 0,540$

The mean wind profile over orography

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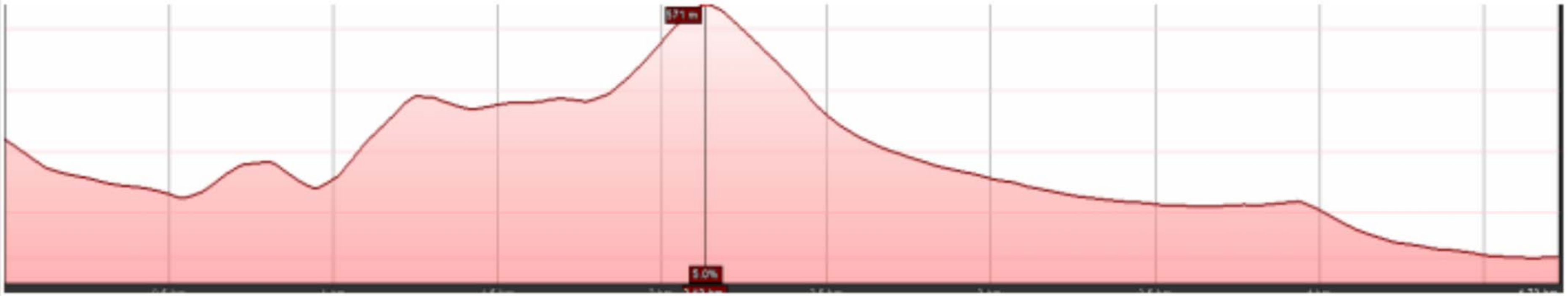
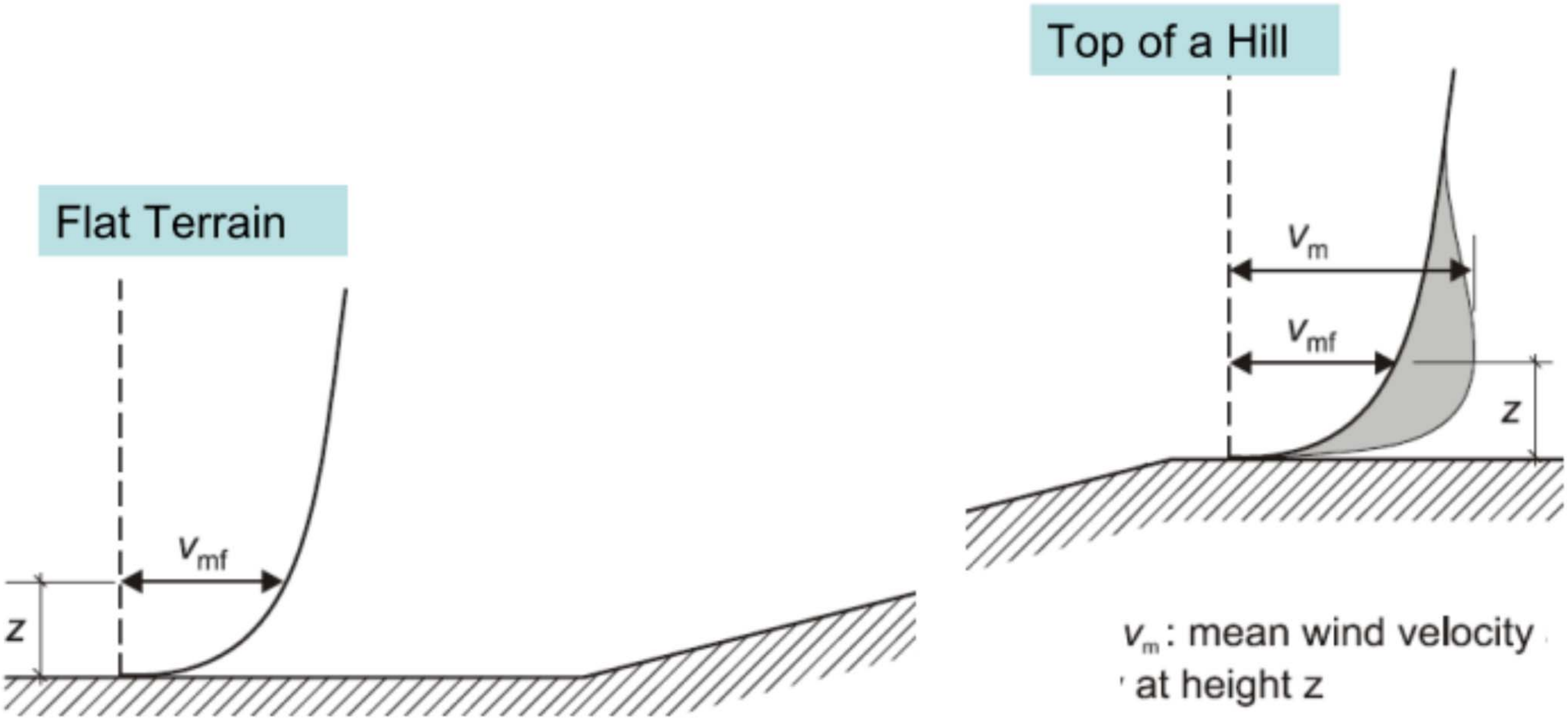


The mean wind profile over orography

The mean wind velocity at height z above ground depends on terrain roughness and terrain contour, the so-called orography



v_{mf}: mean wind velocity above flat terrain

v_m: mean wind velocity at height z

orography factor c_O

$c_O = v_m / v_{mf}$

Turbulence Intensity

The turbulent velocity fluctuations are random in time and space. They have zero mean and a standard deviation σ_v . The standard deviation

- is constant in z,
- is independent of orography,
- depends on the terrain roughness via the terrain factor k_r.

$$\sigma_v = k_r \cdot v_b \quad \text{where} \quad k_r = 0{,}19 \cdot \left(\frac{z_0}{z_{0,II}} \right)^{0{,}07}$$

The turbulence intensity $I_v(z)$ at height z is defined as the ratio of the standard deviation of turbulence and the mean wind velocity.

$$I_v(z) = \frac{\sigma_v}{v_m(z)} = \frac{k_I}{c_o(z) \cdot \ln(z/z_0)}$$

The turbulence factor k_I is 1 in general.
Over flat terrain, the orography factor is 1. Over hills, $c_o > 1$. Then, I_v decreases accordingly.

Peak Velocity Pressure: Exposure Factor c_e

The **exposure factor c_e** is defined through

$$q_p(z) = [1 + 7 \cdot I_v(z)] \cdot \tfrac{1}{2} \cdot \rho \cdot v_m^2(z) = c_e(z) \cdot q_b$$

where $q_b = \tfrac{1}{2} \cdot \rho \cdot v_b^2$ is the basic velocity pressure

The **exposure factor c_e** represents the ***profile*** of the peak velocity pressure referred to the velocity pressure of the mean wind speed at 10m height in flat open terrain.

Considering

$$v_m(z) = c_r(z) \cdot c_o(z) \cdot v_b$$

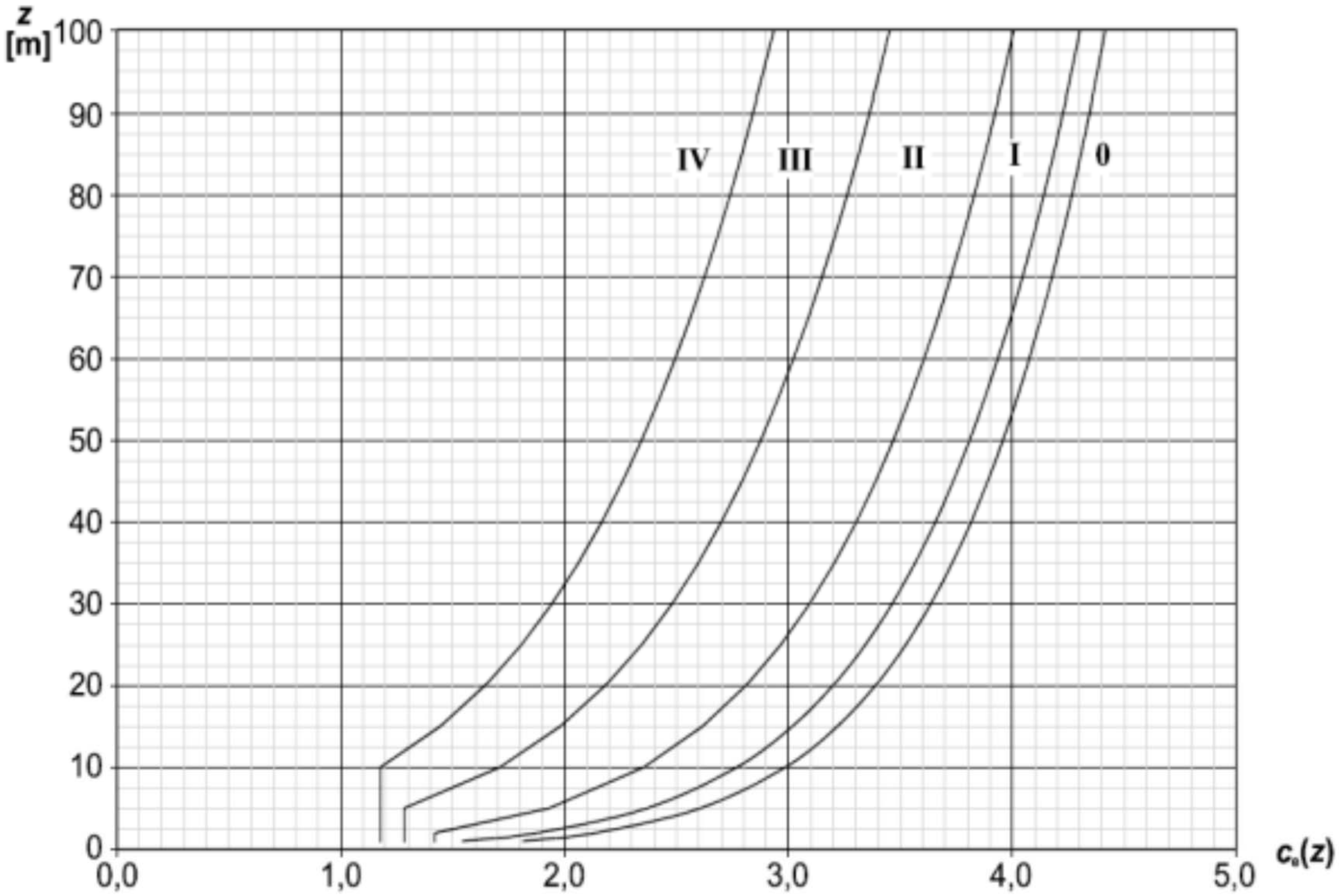
and

$$c_e(z) = \frac{q_p(z)}{q_b}$$

the exposure factor becomes

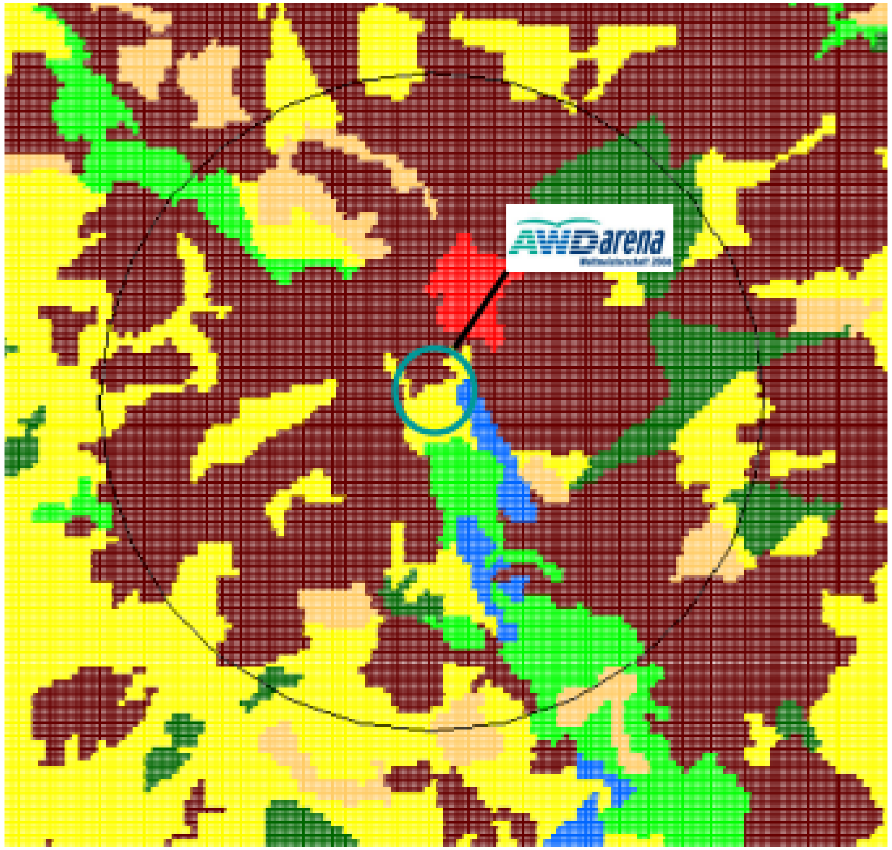
$$c_e = [1 + 7 I_v(z)] \cdot c_r^2(z) \cdot c_o^2(z)$$

Profiles of the Peak Velocity Pressure, q_p

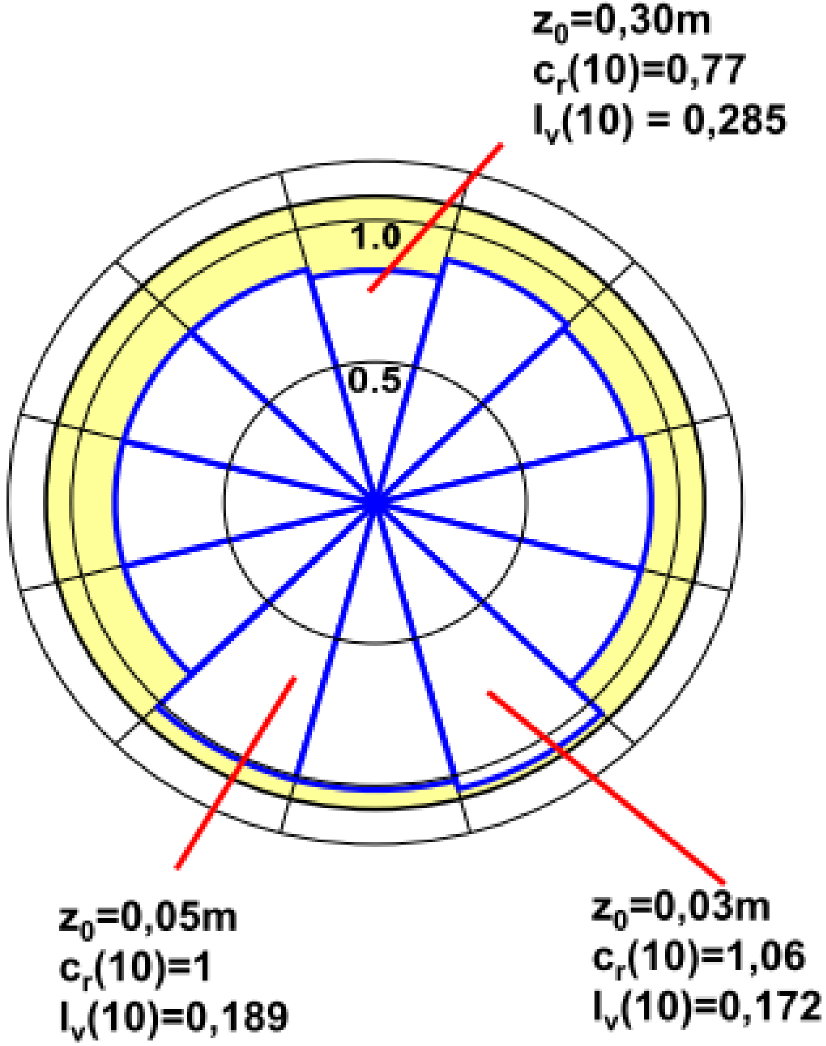


Exposure factor $c_e = q_p/q_b$ for flat terrain

Peak Velocity Pressure: Effect of the Wind Direction



Site of the Stadium in Hannover

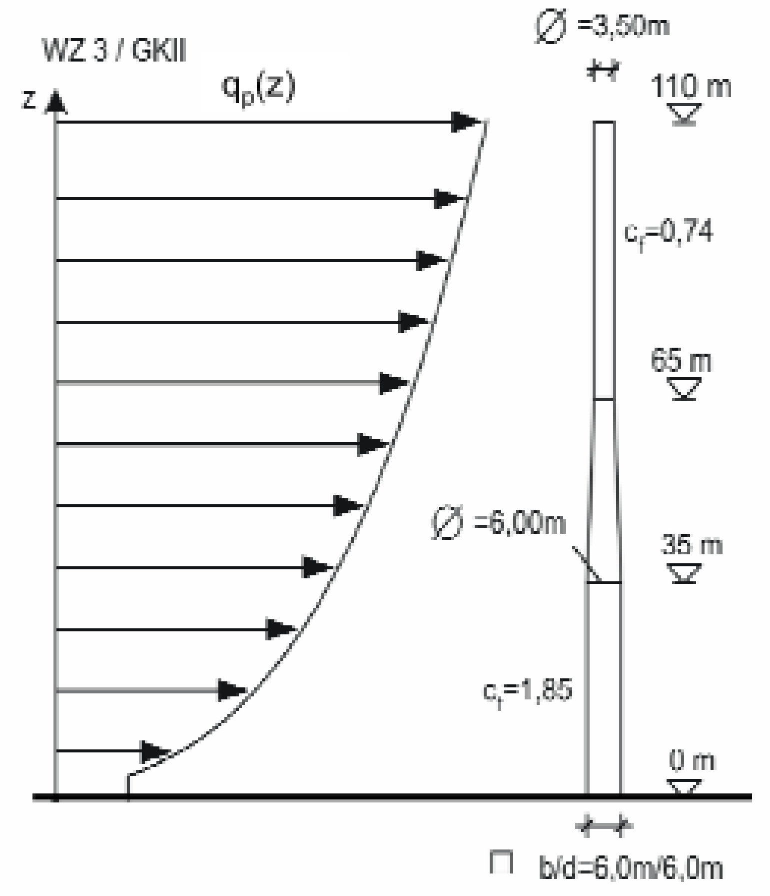


q_p - Rosette at building site at 10m height

Calculation of Wind Forces

Parameter
Wind forces on structures, e.g. for overall wind effects
structural factor: $c_s c_d$
wind force F_W calculated from force coefficients
wind force F_W calculated from pressure coefficients

Wind Forces



EN approach for Wind Forces

$$F_w = c_s c_d \cdot c_f \cdot q_p(z_e) \cdot A_{ref}$$

$c_s c_d$	structural factor
c_f	aerodynamic force coefficient
$q_p(z_e)$	peak velocity pressure at height z_e
A_{ref}	reference area

Wind Forces: Equivalent Static Load Model

$$F_w = c_s c_d \cdot c_f \cdot q_p(z_e) \cdot A_{ref}$$

The wind force specified in EN 1991-1-4, is an *equivalent static load (EQL)* designated to reproduce the true wind action effect, for example maximum displacements or base bending .

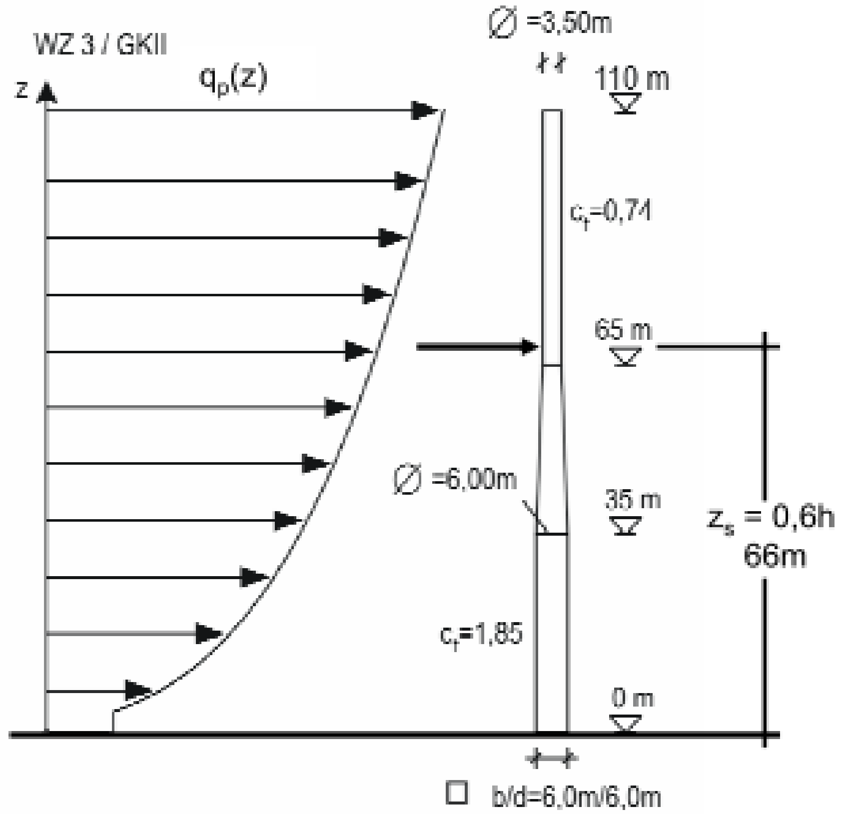
The true wind forces acting at each point of the structural system fluctuate in a stochastic manner. The *EQL* covers the peaks of the response processes induced by the stochastic forces.

The action effect of the true stochastic wind forces is dual:

- The correlation of wind force fluctuations decrease as the dimensions of a building become larger: The load effect diminishes. This so-called size effect is covered by the size factor c_s.

- The wind force fluctuations cause a broad-band dynamic excitation of the structural system. Its high frequency part will cause some resonance with the natural frequencies of the structure, and the load effect will increase. This so-called dynamic effect is covered by the dynamic factor c_d.

Wind Forces – the Structural Factor $c_s\, c_d$



$$c_s c_d = \frac{1 + 2 \cdot k_p \cdot I_v(z_s) \cdot \sqrt{B^2 + R^2}}{1 + 7 \cdot I_v(z_s)}$$

The structural factor is calculated with the turbulence parameters at a particular reference height, namely z_s

Wind Forces – the Structural Factor $c_s\,c_d$ (cont'd)

$$F_w = c_s c_d \cdot c_f \cdot q_p(z_e) \cdot A_{ref}$$

$$c_s c_d = \frac{1 + 2 \cdot k_p \cdot I_v(z_s) \cdot \sqrt{B^2 + R^2}}{1 + 7 \cdot I_v(z_s)}$$

k_p is the peak factor

k_p = ratio of the peak response and its standard deviation

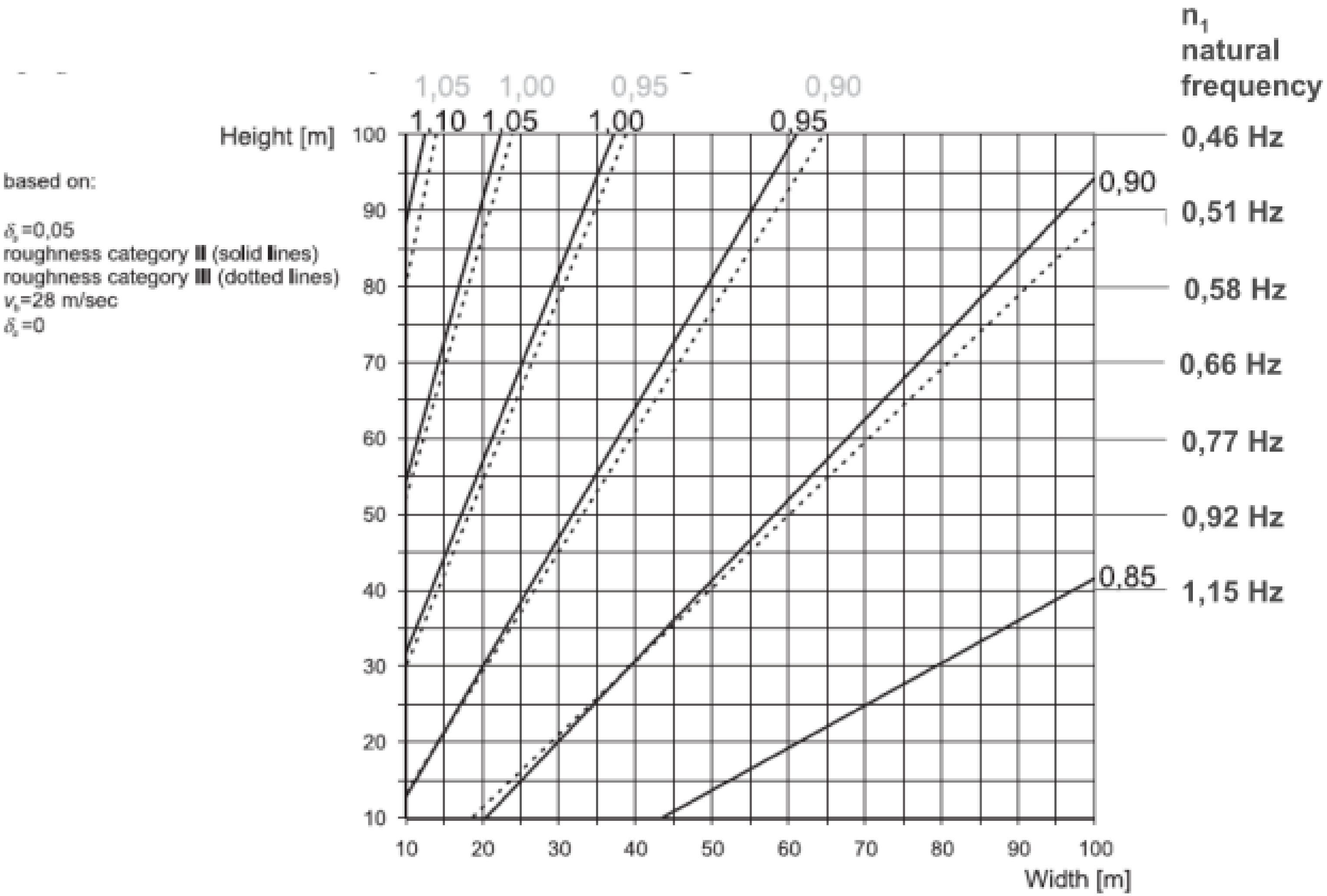
I_v is the turbulence intensity

$B^2 \leq 1$ is the background factor

It allows for the effect of non-simultaneous occurrence of the force peaks on the structure

R^2 is the resonance response factor, allowing for turbulence in resonance with with the vibration mode

Wind Forces – the Structural Factor $c_s\, c_d$ (cont'd)



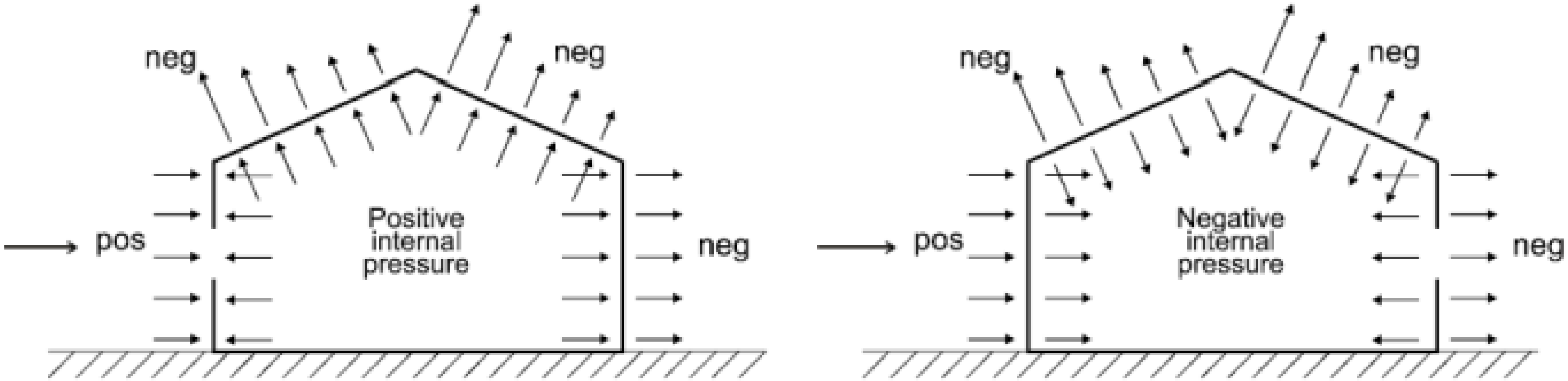
c_s – decreases as height and width increase

c_d – increases as the height increases due to decrease of n_1

Calculation of Wind Pressures

Parameter
Wind pressures, e.g. for cladding, fixings and structural parts
external pressure coefficient c_{pe}
internal pressure coefficient c_{pi}
net pressure coefficient $c_{p,net}$
external wind pressure: $w_e = q_p\, c_{pe}$
internal wind pressure: $w_i = q_p\, c_{pi}$

Wind Pressures: Internal and External



$$w_e = q_p(z_e) \cdot c_{pe}$$

$q_p(z_e)$ is the peak velocity pressure at reference height for the external pressure

c_{pe} pressure coefficient for the external pressure,

$$w_i = q_p(z_i) \cdot c_{pi}$$

$q_p(z_i)$ is the peak velocity pressure

z_i is the reference height for the internal pressure

c_{pi} is the pressure coefficient for the internal pressure

Wind Pressures

Wind Pressures have to be applied if the structural stresses are not correctly reflected when using *wind forces* in the static calculations.

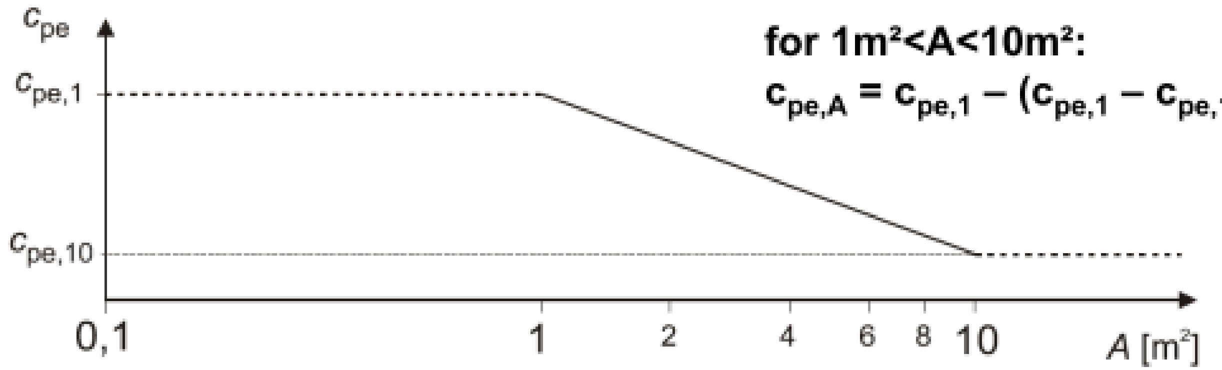
Examples:
Wind forces are adequate for chimneys, whereas pressure distributions are required to calculate the load effects on cooling tower shells, silos, frames …

Wind Pressures are calculated based exclusively on the *peak velocity pressure* q_p. Dynamic effects are not considered.

The size effect is taken into account in the pressure coefficients for loaded areas only in the range between 1 m² and 10 m².

Wind Pressures – Effect of Loaded Area

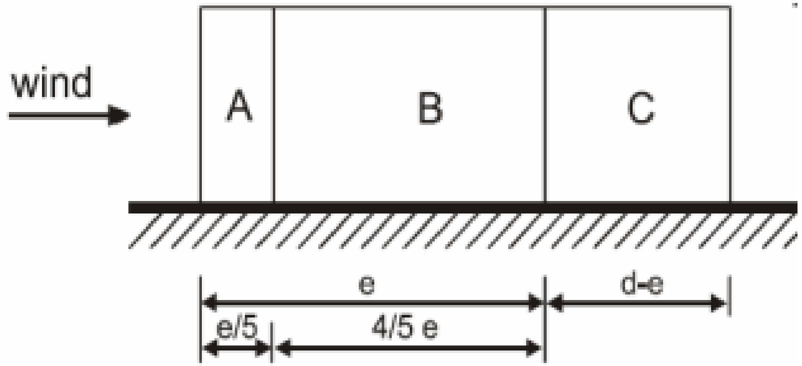
The size effect is considered for loaded areas A up to 10m².



for 1m²<A<10m²:

$$c_{pe,A} = c_{pe,1} - (c_{pe,1} - c_{pe,10}) \cdot \lg A$$

Example: Vertical walls of rectangular plan buildings



e=b or 2h whichever is smaller

Zone	A		B		C	
h/*d*	$c_{pe,10}$	$c_{pe,1}$	$c_{pe,10}$	$c_{pe,1}$	$c_{pe,10}$	$c_{pe,1}$
5	-1,2	-1,4	-0,8	-1,1	-0,5	
1	-1,2	-1,4	-0,8	-1,1	-0,5	
≤ 0,25	-1,2	-1,4	-0,8	-1,1	-0,5	