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WIND ENVIRONMENT AROUND SINGLE BUILDINGS OF RECTANGULAR SHAPE

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Abstract

Wind environment around single buildings and building configurations has been determined, using wind discomfort maps (sand erosion technique) and streamline maps (surface flow visualization). Criteria for wind environment are given, as well as global rules for determining the environment. Photographs of the test results are used to explain the nature of the air stream at walking level around buildings.

WIND ENVIRONMENT AROUND SINGLE BUILDINGS OF RECTANGULAR SHAPE

Preface

On behalf of the Building Research Foundation (SBR) an extended investigation was carried out in the small boundary-layer wind tunnel of IBBC-TNO, to determine the environment around single buildings and building configurations. The extensive results have been published in two SBR-reports [19, 21], both of which have appendices with numerous streamline maps and discomfort maps. The main results and some approximate rules are presented in the next two articles. These articles aim to give architects and town planners a sound basis for design and a method to judge when a wind tunnel test may be necessary.

Fig. 1. Mean hourly wind speed at five observation stations (period 1931-1960). Four speed intervals are distinguished:
0- 3 m/s
3- 8 m/s
8-14 m/s
> 14 m/s
For each sector the percentage of time is shown during which the wind blows in that direction. The wind speed is recorded at a height of 10 m.

Wind environment around single buildings of rectangular shape

1 Introduction

The amount of discomfort people will have to undergo due to wind in a built-up area is highly dependent on the height and the configuration of the buildings in question. This increase in discomfort due to the buildings itself has been recognised for quite some time. In many countries wind tunnel investigations have been carried out to determine the discomfort for a given unfavourable situation. During the last fifteen years several investigators have also tried to formulate general rules to predict the discomfort due to wind and to indicate measures to improve the environment.

At TNO-IBBC some visualizing techniques have been developed to show the results of wind tunnel tests as full-field registration, easily intelligible to architects and town-planners. With the aid of these results general rules for the determination and improvement of wind environment have been determined. In many cases these rules agree fairly well with the results obtained by other investigators, but in some cases the test results prompted us to adopt a quite different approach. In this article the criteria for wind environment and the measuring techniques applied are described, as well as the results obtained for single buildings. The interaction between buildings is treated in the second article.

2 General considerations on wind and wind environment

The Netherlands is a flat and open country with a rather windy climate. The strongest winds blow in directions between south and west, see Fig. 1. The given wind speeds are measured at a height of 10 m, on rather open terrain. At ground level in a built-up area the wind speed will approximately be one-third of these values. The wind speed is reduced near the ground due to the terrain roughness, and this reduction in speed increases with increasing height and density of the built-up area. This means that the average wind speed at walking level in a large city is lower than in a village and this wind speed will in turn be lower than in flat open country, see Fig. 2. This could give the impression that a high and densely built-up area will have a favourable influence. This is only partly true, however. On the one hand, the buildings help to slow down the wind; on the other hand, however, this slowing-down effect will cause a totally different flow pattern around each single building. This influence will be predominant in the direct vicinity of the building, and the gusty character of these air streams may cause quite some trouble and even danger around the high buildings. The effects increase the higher the building rises above the surrounding built-up area.

Wind is accepted as a natural phenomenon, and healthy people will generally not complain about it. But for children, weak persons or elderly people, strong gusts may be

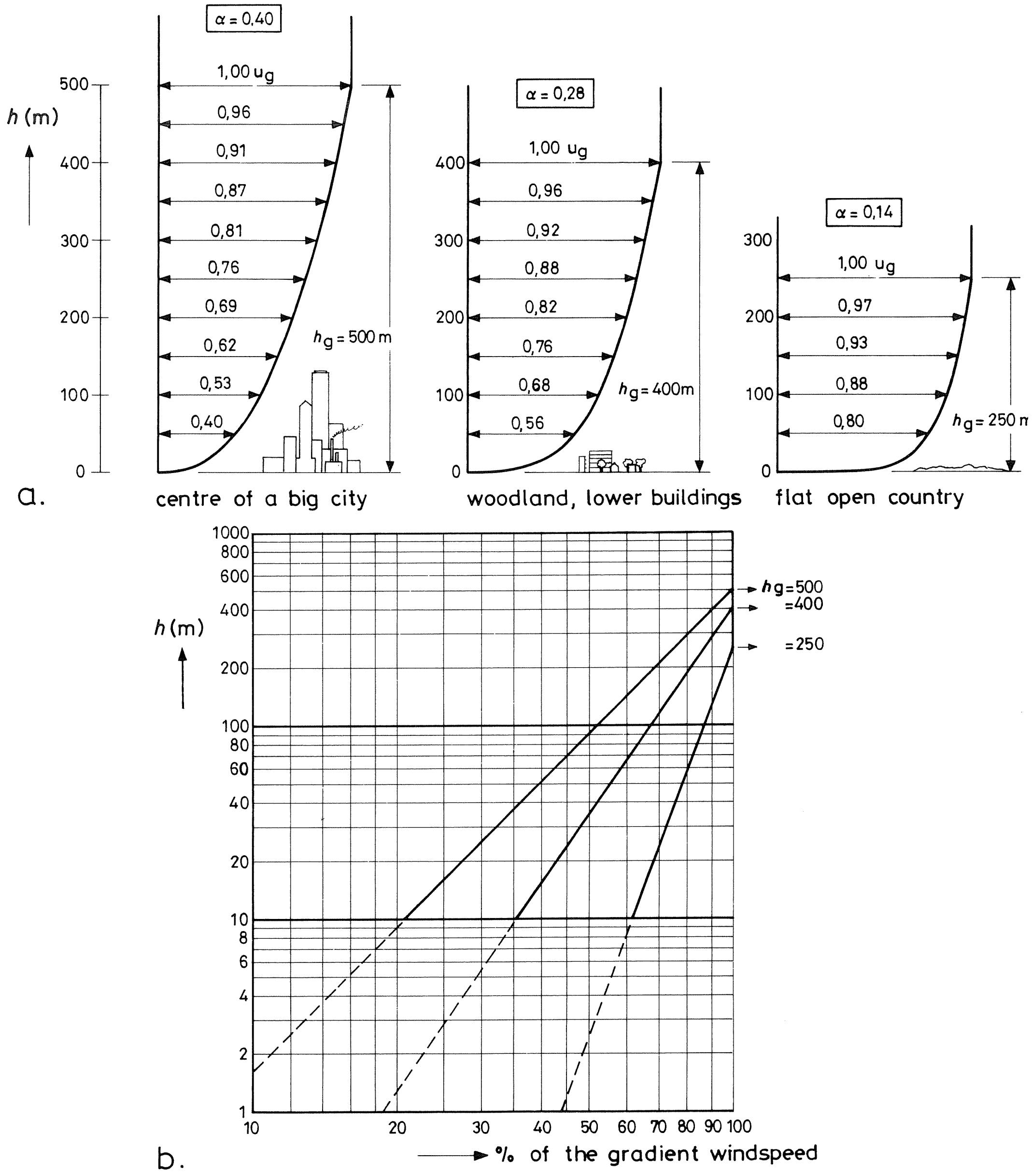


Fig. 2. Average wind speed as a function of height. The wind speed is determined as:

$\bar{v}_h = \left(\frac{h}{h_0}\right)^{\alpha} \bar{v}_0$ for $h < h_g$

$\bar{v}_h = v_g$ for $h > h_g$

in which

$\bar{v}_h$ = average wind speed at a height h

$\bar{v}_0$ = average reference wind speed (for instance at the measuring height of 10 m at the observation stations)

h_g = height of the boundary layer

v_g = (fictitious) constant gradient wind speed

a. Wind speed profile for three kinds of terrain roughness

centre of a big city	$\alpha = 0{,}40$	$h_g = 500$ m
woodland, lower buildings	$\alpha = 0{,}28$	$h_g = 400$ m
flat open country	$\alpha = 0{,}14$	$h_g = 250$ m

b. Wind speed profile according to Fig. 2a, but now shown on a double logarithmic scale.

dangerous. It will be obvious that most people - and especially the above-mentioned category - will try to stay indoors during a severe storm. The situation becomes intolerable, however, if a normal wind is blowing and the air streams suddenly are so greatly increased by the built-up area itself that danger occurs.

The surprising effect of wind is one of its most annoying properties. Only if persons regularly pass through such areas will they gradually learn how to avoid the most affected spots. If the average wind speed decreases, the dangerous aspects will also decrease and will finally disappear completely. Nevertheless such spots will be regarded as uncomfortable as the wind speeds most of the time will be much higher than in the near vicinity.

To create an area in the open air which is so sheltered that no complaints will ever occur is almost impossible. One will always have to accept that, during a certain percentage of time, wind speeds will reach unacceptable magnitudes. It will be obvious that the wind speed at walking level is the most important factor, i.e., in a zone of about two meters above the ground.

Uncomfortable effects will not only be caused by the absolute magnitude of the wind speed but also by the variation in wind speed. This variation is time- and position-dependent. On a certain spot in a built-up area on a windy day, strong variations in wind speed and wind direction will generally occur. During the calmer periods there will hardly be any discomfort; discomfort is entirely determined by the wind speeds during the strongest gusts. But if on walking through such an area, it will be found that at several spots the level of the gusty wind is considerably higher or lower than at the spot first considered.

Abrupt changes in wind speed in the direct vicinity of building corners and in openings under buildings are well known. At such spots one is more or less prepared to be strongly affected, but in general a pedestrian has not the slightest idea what he has to expect from the wind. The variation in wind speed and in wind direction - horizontal as well as vertical - is mostly caused by the various vortexes and causes some considerable discomfort. Flapping clothes, hats blowing away, umbrellas turning inside out are familiar facts. Vertical air streams also raise dust and sand, phenomena which are hardly appreciated by any pedestrian or byciclist. Water may likewise be raised in substantial quantities from ponds or ornamental water round buildings.

3 Criteria for the acceptability of wind speeds

As wind is a stochastic phenomenon, it is usual to give acceptable wind speeds with stated frequency of occurrence. For dangerous situations, gusts with a duration of one to three seconds will be considered critical. Loss of balance will occur within this time and the dimensions of the gusts are large enough to cover the human body completely [1, 2, 3, 4]. In Fig. 3 the adopted criteria for acceptable wind speed are given for four different kinds of area [5, 7]. On the vertical axis is shown the 3 s gust speed, which is approximately 1.7 times the mean hourly wind speed in western Holland. On the horizontal axis are shown the hours per year in which these gust speeds are likely to occur a few times per hour. A basis for comparison is provided by the dotted line which gives the presence of gust speeds as may be expected in western Holland in more or less open country at walking level, see Fig. 3. Obviously the occurrence of these wind speeds has to be accepted anyway if no precautions have been taken to reduce then. Due to the built up area some reduction in these windspeeds may be expected, and if these windspeeds are reduced to 90% of their original value, they will practically coincide with line A, which relates to unsheltered areas. The lines B, C and D relate to situations where gradually more shelter may be expected. The wind speeds obtained from line A are consecutively reduced to 80%, 60% and 40%. In regard to comfort criteria these lines are in fair agreement with the corresponding lines 1, 2, 3 and 4, as given by Davenport [8]. For dangerous situations ($\hat{u} > 20$ m/s) there are great discrepancies, however. But in our opinion, increased shelter in an area requires reduction of all wind speeds, especially the maxima. In this way the comfort criteria can be related to the magnification factors for the gust speed, determined from wind tunnel tests (see 5.1), and the general wind climate as defined by the environmental characteristics (city, village, forest etc.). In Fig. 4 the lines A, B, C, D are repeated and compared with various simple criteria as given by some other investigators [1, 4, 9, 10].

The value $\hat{u}_g$ relates to the critical gust speeds, occurring a few times during one hour per year.

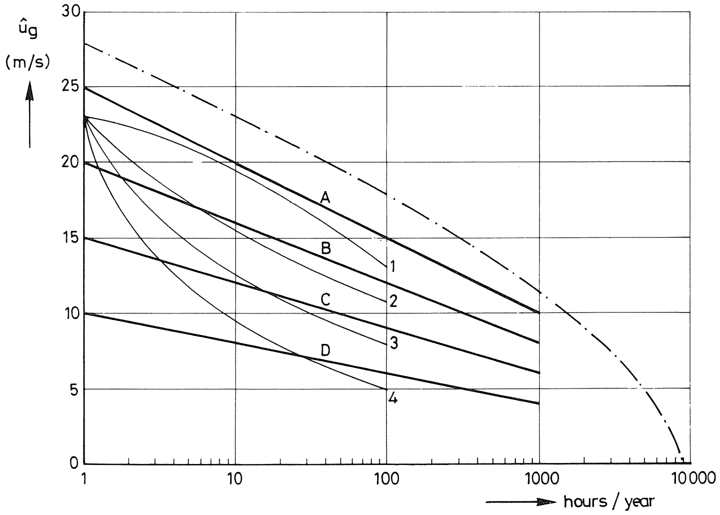


Fig. 3. Criteria for acceptable wind speed ($\hat{u} = 3$ s gust speed).
1, 2, 3, 4 Criteria according to Davenport.
A, B, C, D adopted criteria.
-·- 1,7 × mean hourly wind speed in western Holland.
A no particular shelter (industrial area)
B normal shelter (residential area)
C enlarged shelter (shopping precinct)
D high shelter (infant playgrounds, homes for the aged)

Tabel 1. Lists the various areas and the outdoor activities of the inhabitants. Criteria for environment

code	$\hat{u}_g$	area	activity
A	25 m/s	industrial area, open residential quarter without social functions	walking, cycling passing traffic
B	20 m/s	normal residential quarter with shops and schools; playgrounds	walking, standing cycling standing, sporting
C	15 m/s	local centre with social activities shopping precincts footpaths, parks	walking, strolling, lounging, standing ditto, children playing
D	10 m/s	home for the aged kindergarten terrace	walking, sitting playing, lying sitting

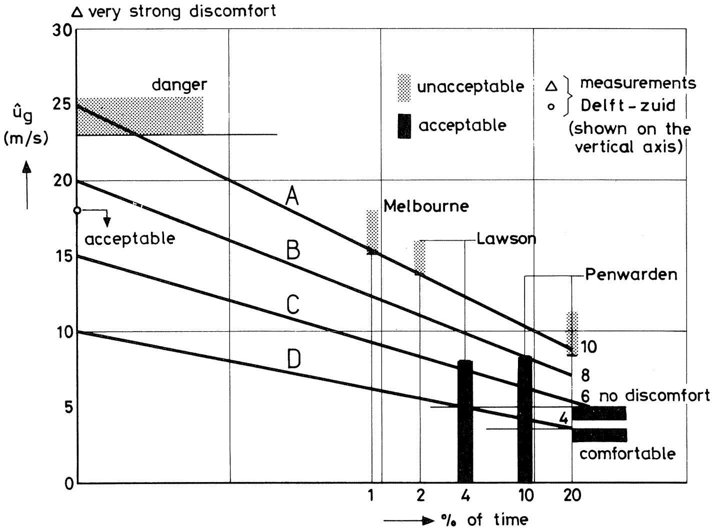


Fig. 4. Comparison of the criterion in Fig. 3 with some simpler criteria as given in the literature. All speeds have been converted to 3 s gust speeds.

4 Wind tunnel tests

All the tests were carried out in a small boundary-layer wind tunnel on a model scale of 1 : 500. The coefficient for the vertical wind profile as shown in Fig. 2 was taken as $\alpha = 0.28$ for all tests.

4.1 *Measuring techniques for the qualities of an air stream*

For a complete description of the wind environment in built-up areas, the variation in the magnitude and direction of the air stream should be known as a function of space and time. In practice, however, there are problems in recording and interpreting of the phenomena. So, in general, just a few aspects are determined, often with various measuring techniques. The following list will give some idea of the phenomena which are determined in wind tunnel tests.

a. The magnitude of the mean wind speed $\bar{u}$.
b. The average wind direction $\bar{\varphi}$.
c. The variation of the wind speed as a function of time, $\tilde{u} = F(t)$, or the turbulence $\tilde{u} - \bar{u}$.
d. The variation of the wind direction as a function of time, $\tilde{\varphi} = G(t)$, or the transverse turbulende $\tilde{v}$.
e. The range in wind speed, i.e., maximum and minimum value of the wind speed, u_{max} and u_{min}.
f1. The magnitude of a reference gust speed $\hat{u}_g$, (a 3-second gust for instance).
f2. The magnitude of a reference speed, dependent on the root mean square, for instance $\hat{u} = \bar{u} + \sigma$ or $\hat{u} = \bar{u} + 3\sigma$.
g. The variation of the mean wind speed, the gust speed of a reference speed as a function of place, $u = f(x,y)$.
h. The occurrence of vertical components of the airstream, u_z.

Measurements in wind tunnels are carried out with the help of various measuring techniques. Some of the most commonly used methods are the following:

Point by point measurements over a limited height
Optical dynamometer (see 4.4).
Hot wire anemometer.
Thermistor.
Tufts.

Continuous measuring techniques at ground level (see 4.4)
Sand erosion technique, see Fig. 5, 6.
Surface flow visualization, see Fig. 7.

Semi-continuous recording in space
Smoke.
Smoke wire recording [11].
Soap bubbles.

In Table 2, a survey is given of the posibilities of the above-mentioned measuring techniques.

Table 2. Possibilities of the measuring techniques

	$\bar{u}$	$\bar{\varphi}$	$\tilde{u}$	$\tilde{\varphi}$	$u_{\max}$	$\hat{u}_g$	$\hat{u}$	u_{xy}	u_z
optical dynamometer	**	***	**	**	***	*			
hot wire anemometer	***		***		***		***		
thermistor	***								
tufts		**		*					*
sand erosion techniques					**	***		***	*
flow visualization		***		*	*	*		*	*
smoke		*	*	**					**
smoke wire	*	*	**	**				*	**
soap bubbles			***		*			*	**

*** gives a complete description of the phenomena
** gives a fair description
* gives some information

4.2 *Comparison of the various measuring techniques*

The optical dynamometer is considered to give the best information on wind environment [5, 6, 12]. The total horizontal force exerted on a human body is measured as a function of time, from which the corresponding mean wind speed over the height of the body is easily deduced. The wind speed is given in magnitude and direction. Time-average readings give a good insight into the variation of the horizontal component of the wind speed, see Fig. 9, where some readings around a building configuration are given.

The quite different behaviour of the air stream at the various points is easily recognised. The maximum and minimum gust speed (dependent on the natural frequency of the measuring instrument) are given as well as the mean wind direction and the turbulence in the longitudinal and transverse direction, all in a condensed form.

The hot wire anemometer will provide very detailed information about certain aspects of the air stream. The wind speed as a function of time is accurately known, and the mean value and the root mean square are easily determined, as well as any desired reference speed $\hat{u}$. There is no information available about the wind direction, however, and when the mean wind speed is relatively low compared with the turbulence, readings are unreliable. However, measuring instruments have been developed which are able to take into account the direction of the wind [13]. Thermistor measurements only provide data about the mean wind speed; neither the turbulence nor the wind direction are taken into account. To obtain some information about the last two phenomena, tufts are applied.

The sand erosion tests give an overall picture of the various phenomena. The erosion is mainly governed by the gust speed, but also by the velocity gradient and the occurrence of vertical components of the air stream. The pattern obtained is regarded as a measure of the wind environment (discomfort parameter), see section 4.4. The variation of the gust speed as a function of place is evident. The method acts as a perfect warning system, as every change in the wind environment, due to a change in the built-up area, is immediately recognised over the whole area.

The flow visualization technique clearly shows the average direction of the wind at ground level. The density and shape of the streamline pattern also provides some information about the turbulence and the occurrence of vertical air streams.

Introducing smoke into the wind tunnel gives a good idea of the movements of the air stream. Smoke-wire and soap bubble techniques also give excellent insight, but these techniques are not always very well suited for numerical evaluation.

4.3 *Suitability of the various measuring techniques for the determination of wind environment*

The question arises as to which phenomena should be investigated to determine the wind environment. An extensive literature exists [7]. Various suggestions have been made, but none seems very certain. It will be quite obvious, however, that not only the mean wind speed but also the gustiness should be considered. As a matter of fact, a pedestrian is only affected by the gusts and generally has not the slightest idea what wind speed should be regarded as the mean wind speed. A person who is affected by a gust of relatively long duration, say 5 to 30 seconds, reacts in the same way as when subjected to a steady wind speed of the same magnitude. Gusts of shorter duration may affect one's equilibrium and can be very dangerous when high wind speeds occur.

Most investigators realize that turbulence should somehow be taken into account. To simplify the readings of the hot wire anemometer, reference speeds are used such as $\hat{u} = \bar{u} + \sigma$, or $\hat{u} = \bar{u} + 3\sigma$. But when the turbulence intensity is high compared with the mean wind speed, the real effect is underestimated. The same thing happens when the phenomena are non-stationary, as often occurs at the corners or in front of a building.

The variation in wind speed is not only a function of time, but also a function of place. A person on foot cannot even distinguish between the two; only at the corners of buildings is the second effect expected. Losing one's balance is greatly affected by these phenomena. In normal investigations, the distance between the point-by-point measurements is much too large to determine this variation in wind speed as a function of place, only overall measuring techniques are applicable.

Another effect of gustiness is the variation in wind direction, horizontal as well as vertical. Minor variations in wind direction are taken into account by the transverse turbulence intensity, but a complete reversal of the wind flow is not detected by most measuring instruments. The optical dynamometer, however, gives complete insight into the variations of the horizontal components of the wind speed.

Particularly this variation in wind direction and magnitude causes considerable discomfort.

4.4 *Chosen measuring techniques*

To obtain a good insight into the air streams around buildings at walking level, the magnitude of the gust speed as well as the wind direction should be known, not only at a few selected points, but over the whole area of interest.

The measurements should be carried out quickly and the results should be easily intelligible to architects and town planners. This leads automatically to the overall measuring techniques at ground level as described in Section 4.1: the sand erosion technique and the surface flow visualization.

The sand erosion tests have been chosen as the main tests to determine the wind environment, as they cover the three main aspects of the disturbance:

a. The phenomena are mainly governed by the horizontal gust speed.
b. The turbulent areas and the variation in wind speed as a function of place are recorded over the whole area.
c. The influence of vertical air streams is recognised.

If the phenomenon were determined only by the horizontal gust speed, magnification factors for the gust speed would be obtained, i.e., the ratio between the local gust speed around the building and the gust speed at the same point without the presence of the building. But as the other phenomena also influence the sand erosion, it is preferable to replace the term magnification factor by the term discomfort parameter. In similar circumstances Gandemer used the word "comfort parameter" [14, 15].

The flow visualization technique gives excellent insight into the average wind direction and also yields some information on the turbulence of the air flow. It is our opinion that for a full understanding of the phenomena, sand erosion tests and streamline patterns should be regarded together. Most of the time there will still remain some places where it is difficult to understand why the results of the tests are as they are. The application of the optical dynamometer will then generally solve most of the problems. Only when strong vertical air straims occur will the sand test give values which could be overestimated. To see what really happens, field measurements around heavily affected buildings should be carried out.

5 Experimental techniques

5.1 *Sand erosion tests*

The erosion of sand, sprinkled at ground level in the tunnel, is used as an indication of wind environment [5, 6, 16, 17]. As the phenomenon is mainly governed by the horizontal gust speed, quantitative data can be obtained as follows.

For calibration the ground level of the measuring section (without a model) is sprinkled with dried sand (particle diameter 0.1–0.2 mm, thickness of the layer about 0.4 mm). The wind tunnel speed is increased in steps, each lasting 2 minutes. When the mean wind tunnel speed at a reference height h_r (100 m in reality) reaches a certain value $\bar{u}_r$ (= 6 m/s for the chosen sand diameter), the sand on the ground is blown away. This is due to the gusts during the 2 minutes' measuring time.

For measuring purposes, a model is placed in the tunnel and the ground is again sprinkled with sand. The mean wind speed is increased in steps, each of 2 minutes' duration during which the sand is blown away around the model over even larger areas. If it is assumed that the sand always is blown away by the same gust speed, magnification

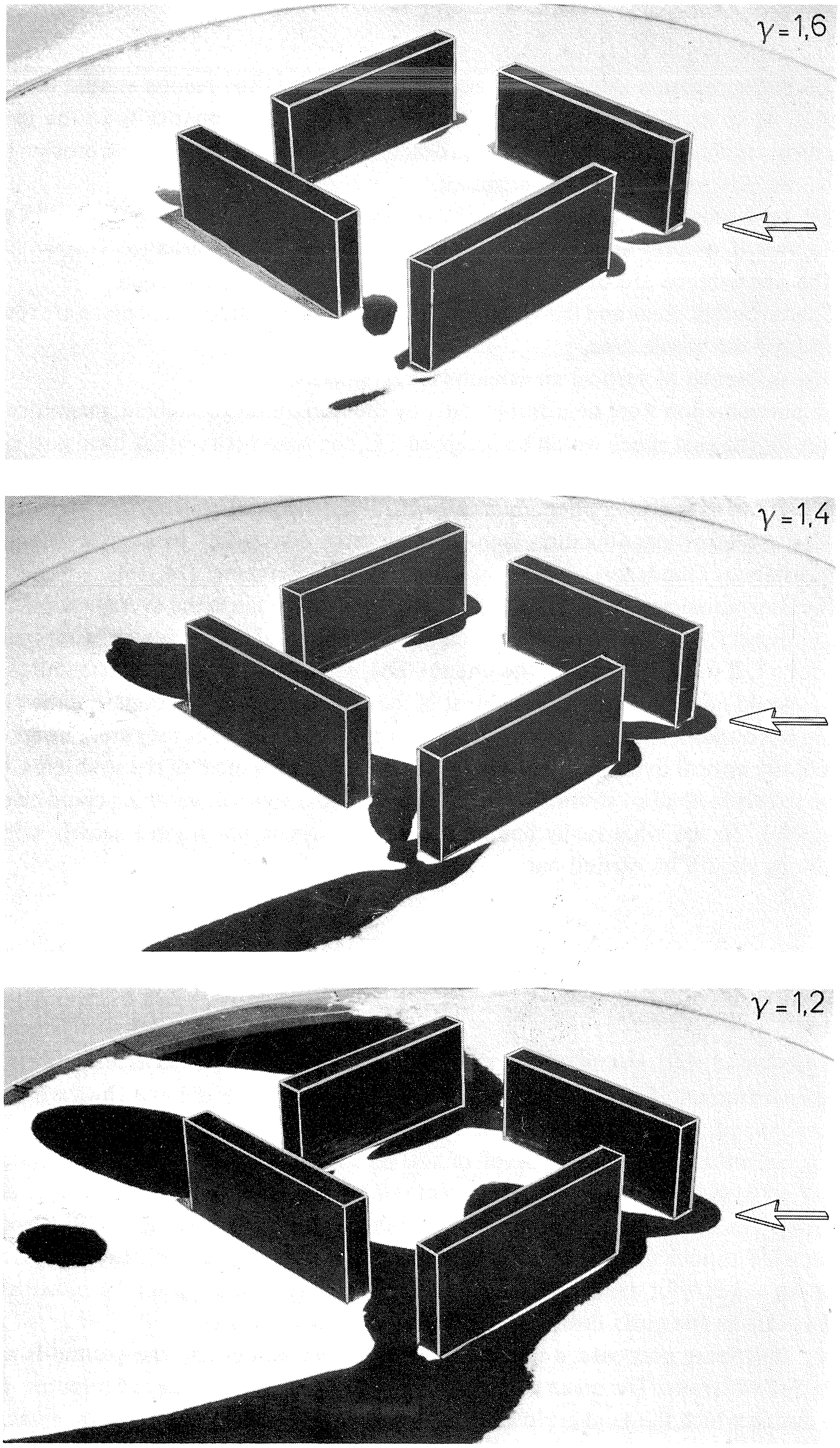


Fig. 5. Three consecutive steps in a sand erosion test $\gamma = 1{,}6 - 1{,}4 - 1{,}2$. Configuration of four slab blocks; $b \times l \times h = 10\ \text{m} \times 80\ \text{m} \times 50\ \text{m}$.

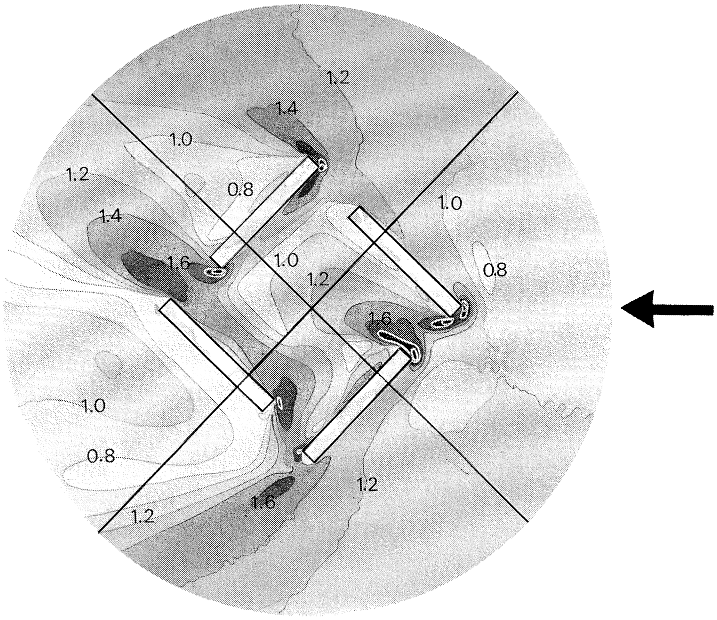


Fig. 6. Contour line map for the discomfort parameter. Same configuration as in Fig. 5.

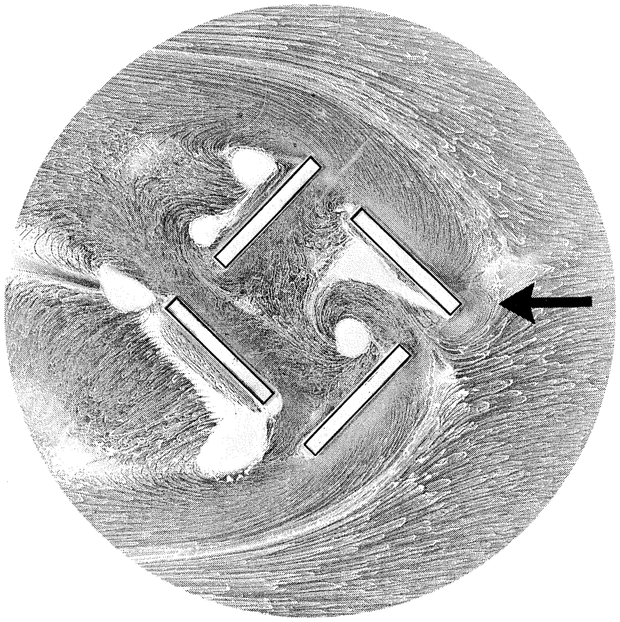


Fig. 7. Streamline pattern. Same configuration as in Fig. 5.

factors for the gust speed can be determined as follows. If, for instance, somewhere sand is blown away when the mean wind speed equals $\overline{u} = 4$ m/s, then the gust speed in that particular area is increased by a factor $\gamma = \overline{u}_r/\overline{u} = 6/4 = 1.5$. As the erosion of the sand is also influenced by some other factors which are important for the environment, the factor γ will be called the discomfort parameter instead of the magnification factor.

Photographs are taken after each step, see Fig. 5. The reproducibility of the phenomenon is excellent. In general, photographs are taken for the factors $\gamma = 3.0, 2.5, 2.0, 1.8, \ldots, 1.0, 0.8, 0.6$. The corresponding mean wind tunnel speed equals $\overline{u} = \overline{u}_r/\gamma$. A contour line map of the discomfort parameter is obtained with the help of a second camera, where the consecutive exposures are made on the same negative, see Fig. 6. To obtain the same pattern when repeating a test, the two-minute time-scheme should be strictly complied with. If it is desired to obtain the pattern for just one particular value of γ, the foregoing steps may be omitted when the measuring time at the previous step is doubled. Then after 4 minutes almost the same effects are obtained.

It is quite obvious that the phenomena will change when the sand particle diameter is changed. But the main effect will remain the same, and the most important point is that always two situations have to be compared, one without buildings and the second with buildings, or one situation with a certain building configuration and a second situation with an altered building configuration.

5.2 *Surface flow visualization*

The mean direction of the wind at ground level is visualized by a surface flow technique, as is usual in aeronautical wind tunnels, and lately also in boundary layer wind tunnels [14, 16, 18]. The ground is coated with a mixture of kaolin and paraffin oil. Due to the air flow, the mixture is driven over the ground surface while the paraffin oil evaporates. The resulting pattern shows the direction of the airflow at ground level, see Fig. 7. It is most instructive to make a video recording of the test; the most affected areas are then immediately recognised. But even after the test has been completed, the pattern will also give some indication of regions with increased and decreased air speed. The stagnation point in front of a building is easily recognised and all the white spots in the photograph indicate areas where an accumulation of dust, sand and rubbish may be expected.

5.3 *Optical dynamometer*

The optical dynamometer consists of a cylinder on top of a spring, see Fig. 8a [5, 6]. The cylinder has a height of 4 mm and a diameter of 2 mm, and represents a human body on a 1 : 500 model scale. For recording, a mirror is attached to the top of the cylinder, and the reflection of a laser beam is photographed, see Fig. 8b. The instrument acts as a single mass-spring system with viscous damping. When the damping is chosen as semi-critical, wind frequenties lower than the natural frequency of the instrument give displacements (rotations) of the cylinder which are practically proportional to the exerted wind force ($F = \frac{1}{2}\varrho u^2 A C_d$), see Fig. 8c. The effect of higher frequencies is eliminated to a great extent. Most readings have been made with a measuring instrument which had a natural frequency of 12 Hz; so on a 1 : 500 scale only gusts with a longer duration than 40 s are fully taken into account. The main advantage of the instrument is that it supplies the wind force over a total height of 2 m, which is of interest for the wind environment. When time-average recordings are made, data are obtained in a clear condensed form, see Fig. 9.

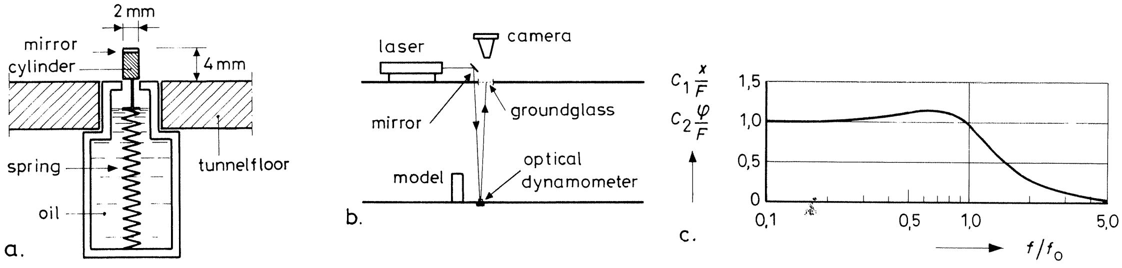


Fig. 8. Optical dynamometer:
- a. measuring instrument
- b. set-up in the wind tunnel
- c. relation between the displacement x (and the rotation φ) of the cylinder and the wind force exerted for semi-critical damping; C_1, C_2 = constants; f = frequency of the wind; f_0 = natural frequency of the dynamometer.

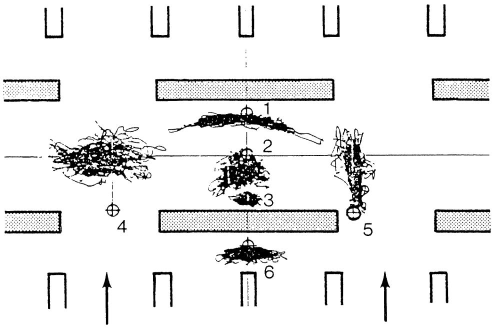


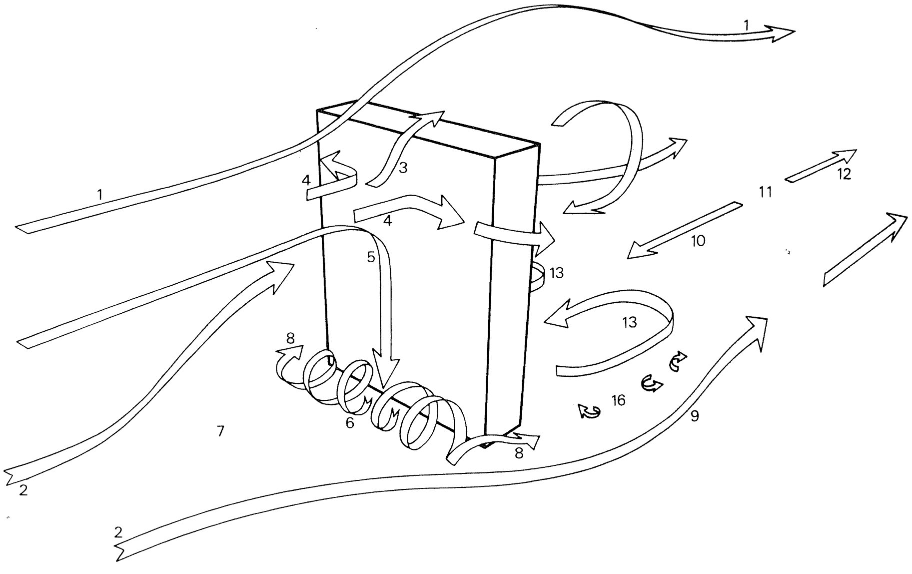
Fig. 9. Time-average optical dynamometer readings not only show the magnitude and direction of the wind but also characterize the kind of air stream. Configuration of high-rise slab blocks (10 m × 80 m × 50 m) amidst much lower buildings:
1. strong transverse air streams in the main street, perpendicular to the wind direction and completely reversing in direction
2. reverse air flow towards the windward building with fairly considerable transverse turbulence
3. high shelter with low wind speeds in all directions
4. more or less constant wind speed in the opening between the two buildings, but rather variable in direction
5. strongly directed wind speed with one strongly predominant direction at the corner of the building, but highly variable in magnitude, i.e., a very gusty wind
6. reverse air stream in front of the building, with fairly considerable transverse turbulence

5.4 *Potential of the full-field measuring techniques*

The potential of the overall measuring techniques is demonstrated for a case where the flow pattern is well known. In Fig. 10 the air stream pattern is given for a high building, with the following dimensions $b \times l \times h = 20 \times 80 \times 70$ (m). The numbers in the diagram each indicate a certain aspect of the air flow, and several of these aspects can be recognised in one of the two photographs or even in both photographs.

It should be home in mind that in these and all following photographs the wind is always blowing from south to north.

0	undisturbed wind (b)
1, 2	air flow over and around the building (a, b)
3, 4	air flow in front of the building is partly deflected above and aside (a)
5	the larger part of the air flow in front of the building is deflected downwards (a)
6	vortexes in front of the building; the main stream at ground level is away from the building (a, b, c)
7	stagnation point in front of the building (a, b, c)
8	strongly increased wind speed at the corners of the buildings (a, b, c)
9	broad jet streams with increased velocity next to the building (a, b, c)
10, 14	reversed air flow behind the building (a, b, c)
11	stagnation point behind the building (a, b, c)
12	air stream in the direction of the wind behind the rear stagnation point (a)
13	standing vortexes behind the building (a, b)
14	increased discomfort in the reversed air stream (b, c)
15	upward-directed air streams behind the building (b, c)
16	small fast rotating vortexes (a, b)
17	edge of the "influence area" (b)



a

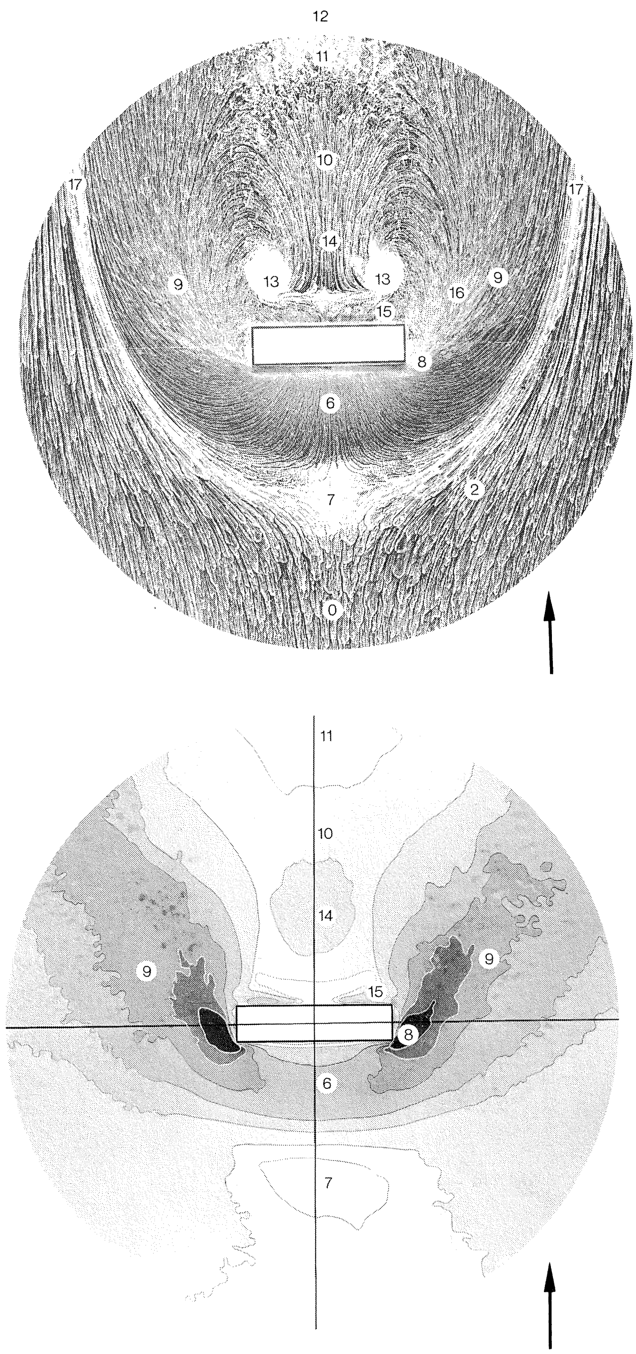


Fig. 10. Wind environment around a high building
a. stylized air flow pattern
b. streamline pattern at ground level (flow visualization)
c. discomfort pattern (sand erosion test).

6 Tests on single buildings

6.1 *General*

An important part of the investigation concentrated on tests relating to single rectangular buildings for several reasons [6, 19]:

a. Most buildings have a rectangular shape.

b. The wind profile and turbulence intensity are caused by the vegetation and built-up area together, but around each building the air flow is mainly influenced by the building itself. So, first of all, the phenomena around a single building should be fully understood before the interaction of buildings is investigated.

c. In many cases high buildings are erected for apart or in the vicinity of much lower buildings. The influence of the high building is then predominant and the worsening effect of this building is practically the same as if the lower buildings were not present. An example is given in Fig. 11, where a tower block is situated amidst a regular configuration of much lower buildings.

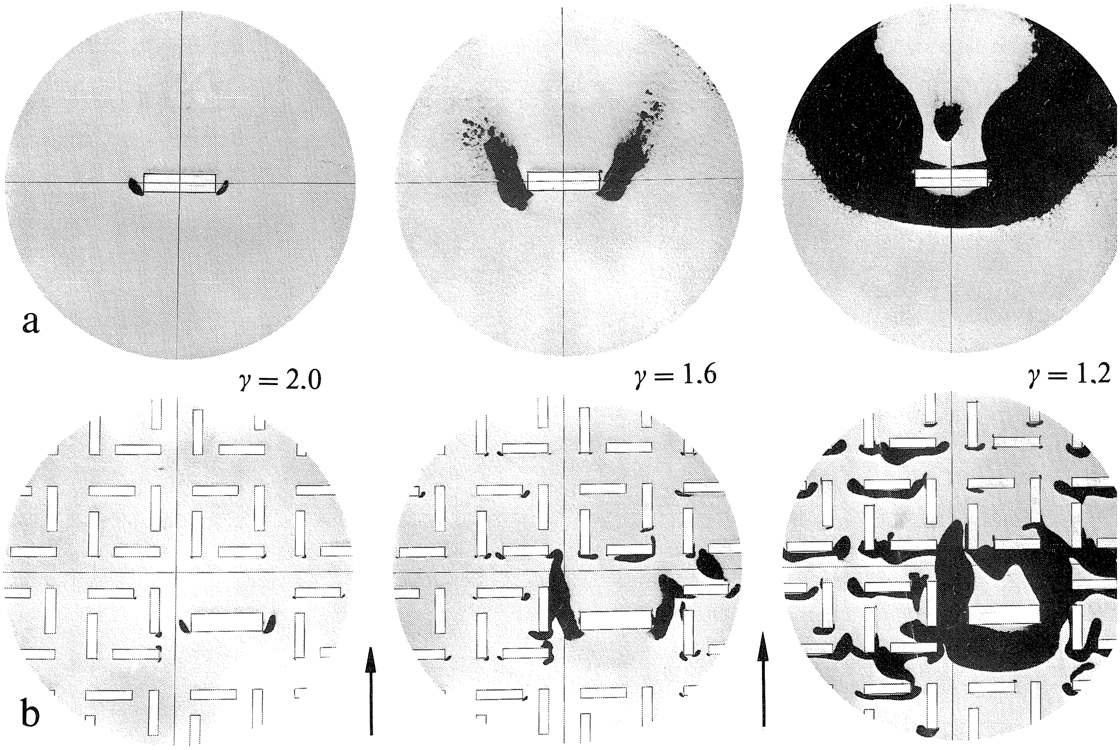


Fig. 11. Comparison of the discomfort areas for a high building alone and the same high building but now surrounded by much lower buildings. The discomfort areas are given for $\gamma =$ 2.0-1.6-1.2.

a. Patterns for the high building alone ($b \times l \times h = 20$ m × 70 m × 70 m).

b. Patterns when the high building is surrounded by a regular configuration of much lower buildings ($b \times l \times h = 10$ m × 50 m × 12 m).

For $\gamma = 2.0$ and $\gamma = 1.6$ the areas in Fig. a and b are practically the same, only for $\gamma = 1.2$ the sheltering effect of the lower buildings is clearly manifest.

d. In many cases the interaction of high buildings is of minor importance and the situation can be regarded more or less as a superposition of the situations which would exist for each of the buildings. A striking example is given in Fig. 12, where two buildings in a rectangular configuration were tested.
There are important exceptions, however, especially due to the occurrence of transverse air streams between buildings.

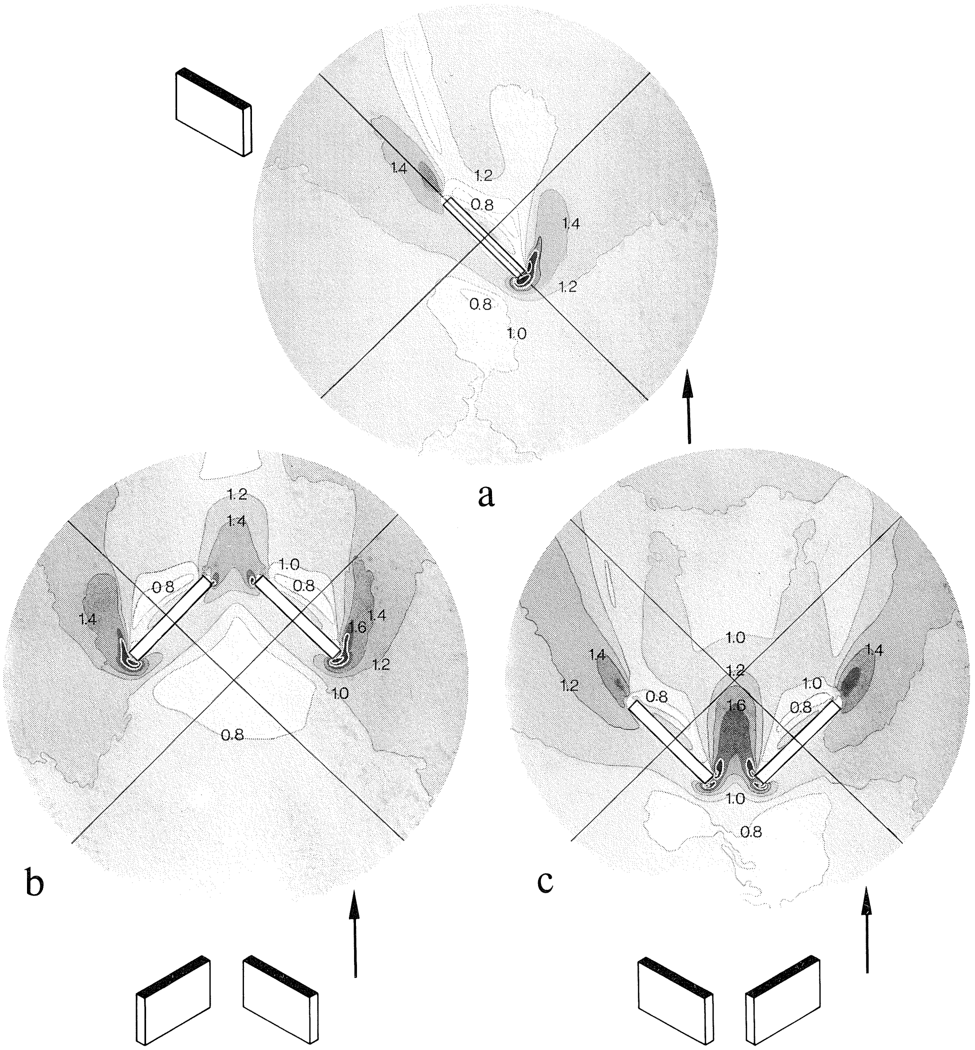


Fig. 12. Building configurations with low interaction.

a. Single building ($b \times l \times h = 10$ m × 80 m × 50 m), discomfort map for wind at 45°.

b. Two buildings in an "open V-shape" where the wind is assumed to cause the so called "Venturi-effect".

c. The same two buildings but now with wind from the opposite direction.

A comparison of the three discomfort maps shows that the main effect for Fig. b and c can be obtained by "superposition" of the discomfort map for Fig. a and its mirrored image.

6.2 *Air flow around rectangular buildings*

The air flow around rectangular buildings is well known if the wind is parallel to one of the main axes of the building. Three wind regimes can clearly be distinguished [14, 16].

a. Tall slender buildings, see Fig. 13a.
The air flow is mainly transported alongside the building and reverse air flows on the windward and leeward side of the building occur only over small areas.

b. Tall buildings of the transitional type, see Fig. 13b.
The air flow on the windward face of the building is to a great extent transported downwards, causing a strong vortex flow and considerable corner streams. On the leeward side of the building a large area with reverse air flow occurs.

c. Long buildings, see Fig. 13c.
The air flow is mainly transported over the building. The vortex flow on the windward side of the building and the corner stream are less pronounced than in the previous case. There is a large area on the leeward side of the building with reverse air streams. When the angle of incidence of the wind is between 30° and 60° with the axes, a vortex "rolls over the building", see Fig. 13d.

The stylized air flow patterns in Fig. 13 are only dependent on the ratio between the main dimensions of the building $(b:l:h)$, i.e., as long as the velocity profile is of the exponential type: $\overline{u}_1 = (h_1/h_0)^{\alpha}\overline{u}_0$.

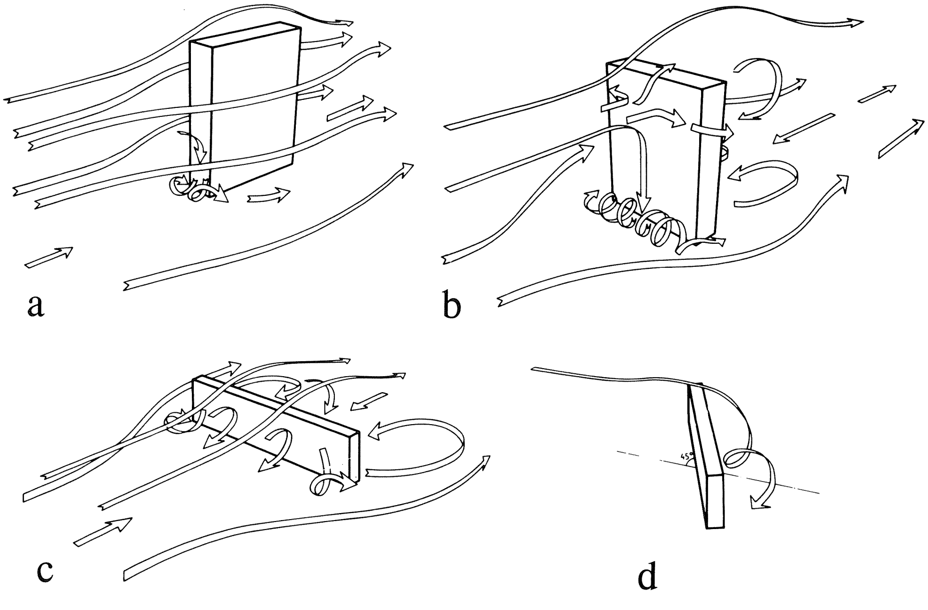


Fig. 13. Stylized air flow patterns around three types of buildings.
a. Tall building.
b. Tall building of the transitional type.
c. Long building.
d. Long building, wind direction $\varphi = 45°$.

A linear magnification of all the dimensions of the building will also cause a linear magnification of the streamline pattern. The discomfort pattern will show a similar shape. However, the discomfort parameter will increase with increasing dimensions of the building.

This means that especially the visualization of the air flow pattern at groundlevel is suited for determining the area in which the air flow is mainly influenced by the building itself. This influence area is chosen as equal to the horse-shoe shaped pattern which is clearly shown in all the flow visualization photographs, see Fig. 10b. In this influence area the turbulence is higher than outside it, and reverse air streams may occur.

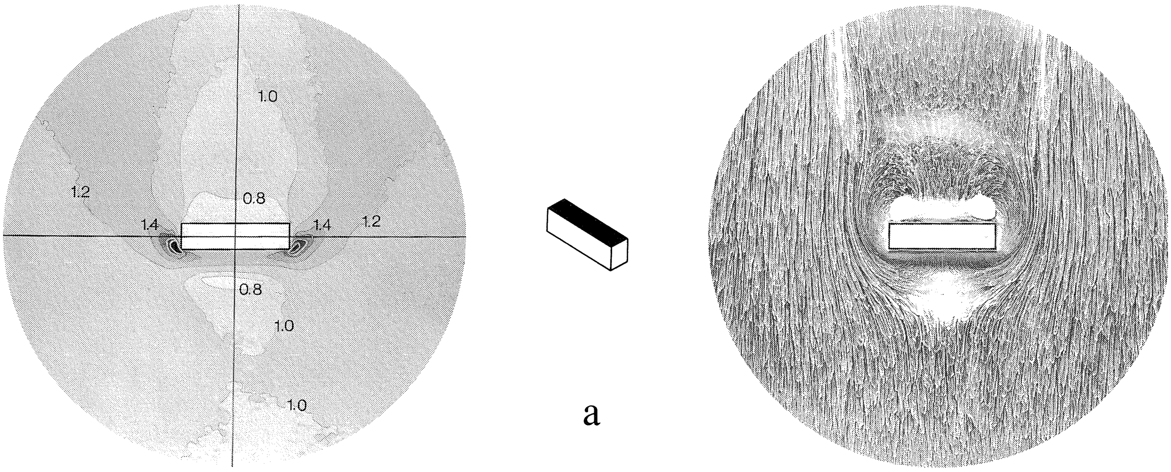
6.3 *Complementary criterion for wind environment*

All modern criteria for wind environment are based on allowable wind speeds with stated frequency of occurrence [7]. In most investigations the disturbance due to the wind is given as a non-dimensional coefficient. By means of this coefficient some reference wind speed in the new situation is compared with the reference wind speed at the same point in the previous situation. Sometimes mean wind speeds are compared, sometimes reference wind speeds such as $\hat{u} = \overline{u} + 3\sigma$, or $\hat{u} = \overline{u} + \sigma$, as has been done by Gandemer [14, 15], introducing the so-called comfort parameter. In principle, gust speeds are compared in the sand erosion tests, and the discomfort parameter should primarily be considered as a magnification in gust speed.

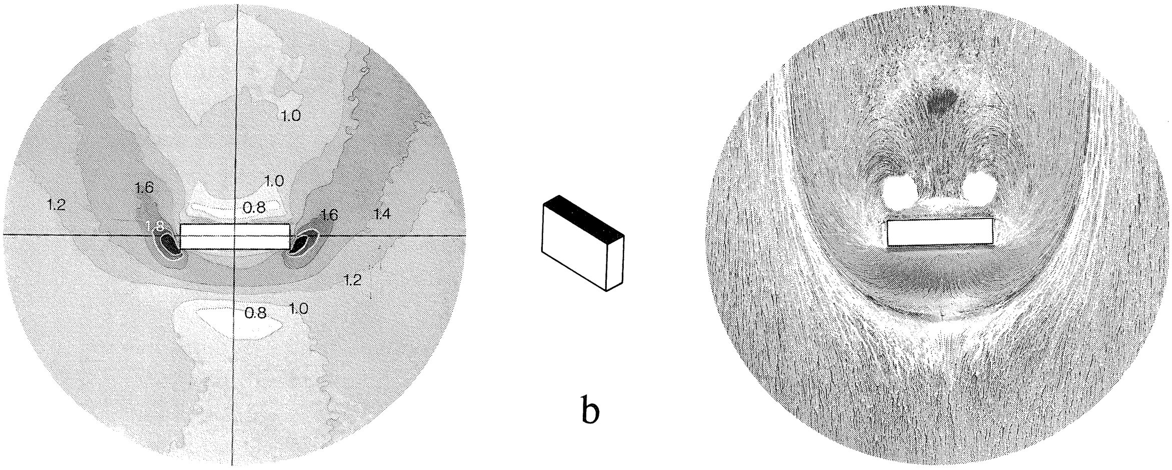
All these approaches are more or less similar and the results are broadly comparable. But if measurements are carried out on a point-by-point basis, one can only hope to have used enough measuring points to detect the worst spots. The results of the sand erosion tests have shown that practically always - even with medium-high buildings - somewhere a discomfort parameter of magnitude 2 will be reached, sometimes over very small areas. This will be quite obvious if it is borne in mind that even in a laminar two-dimensional airflow around a cylinder the maximum wind speed will be twice the mean value [20].

Tests have shown that the maximum value of the discomfort parameter increases very gradually with increasing height of the building, see Fig. 14. As is shown in [7] this maximum value can be connected with the criterion in Fig. 3 if the statistical distribution of the mean hourly wind speed is known. The area in which the discomfort parameter exceeds given values, however, increases very rapidly with increasing height of the building, see Fig. 14b. So it was decided that the magnitude of the area in which the factor γ exceeds given values is of more importance to the environment than the value of $\gamma_{\max}$ itself. As a measure for the environment, the area has been chosen in which the discomfort parameter exceeds the value $\gamma = 1.6$, see Fig. 14c. This magnification of the gust speed is great enough to be significant, and for single buildings this area always belongs to the two jet streams starting from the windward corners. Furthermore, the areas considered are large enough to allow some conclusions to be drawn with confidence.

From the tests it follows that the height of the building is of major importance to the


1.0
1.2
0.8
1.4
1.4
1.2
0.8
1.0
1.0

a


1.0
1.0
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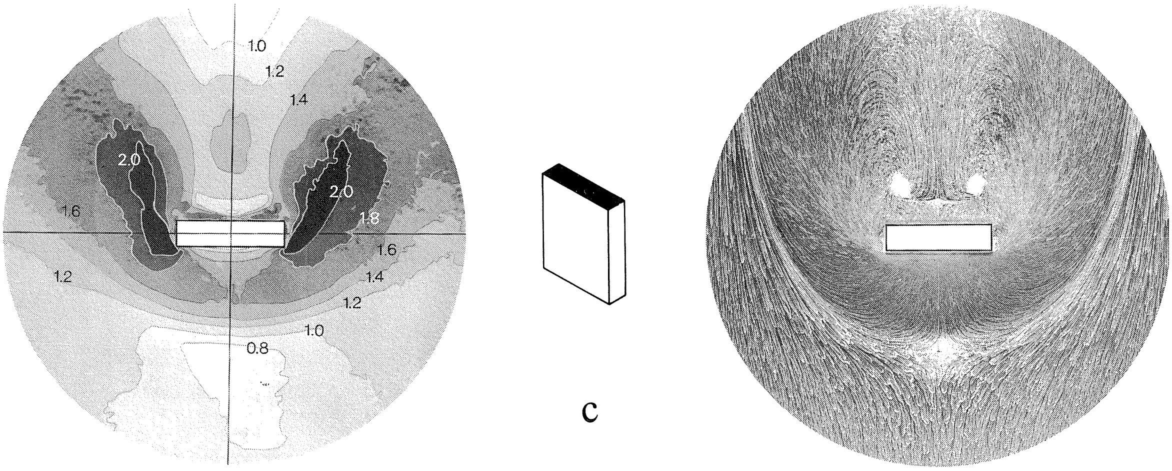
1.0

b


1.0
1.2
1.4
2.0
2.0
1.6
1.8
1.6
1.2
1.4
1.2
1.0
0.8

c

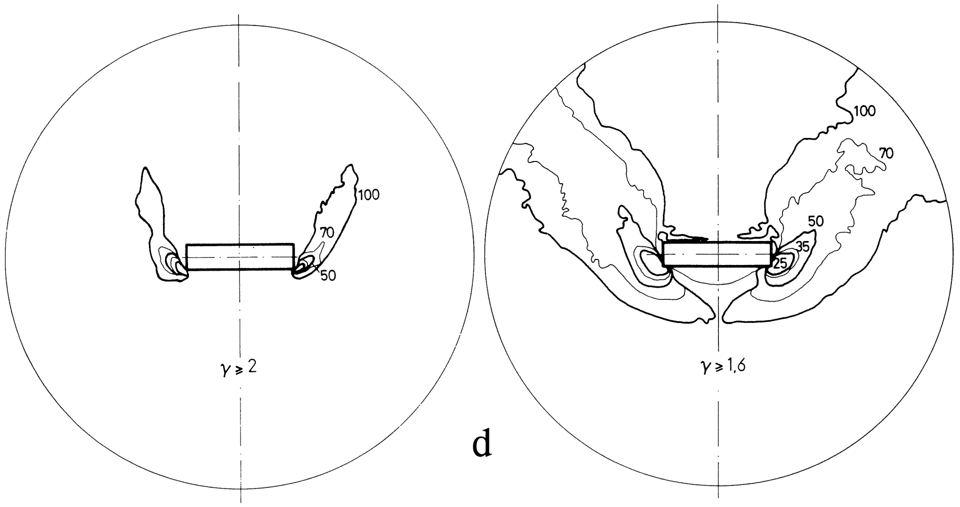


Fig. 14. Influence of the height of a building with dimensions of 20 m × 80 m on plan.
a. Discomfort and streamline map for a height of 25 m.
b. Ditto for a height of 50 m.
c. Ditto for a height of 100 m.
d. Areas in which the discomfort parameter exceeds the values $\gamma = 2.0$ and $\gamma = 1.6$ for a height of 25-35-50-70 and 100 m.

environment, see Fig. 14, where for the same ground plan of a building the height has been increased. The photographs show that the influence area slowly increases, but that the areas where the discomfort parameter exceeds given values, increase very rapidly. The length of the building is also of some importance, as is shown in Fig. 15, where a tower block, a medium-long but high slab block and a long but medium-high slab block are compared. If the wind is perpendicular to the longitudinal direction of the building, the discomfort maps have more or less a similar shape. For wind at 45° the discomfort patterns are more varied. Especially the vortex that "rolls" over the long building in Fig. 15c is clearly visible ("bar"-effect [14]).

The width of the building (width = parallel to the wind) proves to be hardly of importance.

In Fig. 16, for the tower block and the medium-long but high slab block, the area A is given where the discomfort parameter exceeds the values $\gamma = 1.6$-1.8-2.0. The wind direction has been changed in steps of 15°. Especially in the case of the tower block the effect of the "streamline shape" for $\varphi = 45°$ is obvious. For the slab block this effect is hardly discernible. But in both cases the whole situation is fairly well defined if the effects are known for wind parallel to the axes. If A_x^* and A_y^* denotes the average for $\gamma = 1.6$, the areas for other directions can be roughly approximated with the formula

$$A_\varphi^* = \frac{A_x^* + A_y^*}{2} + \frac{A_x^* - A_y^*}{2} \cos 2\varphi \qquad (1)$$

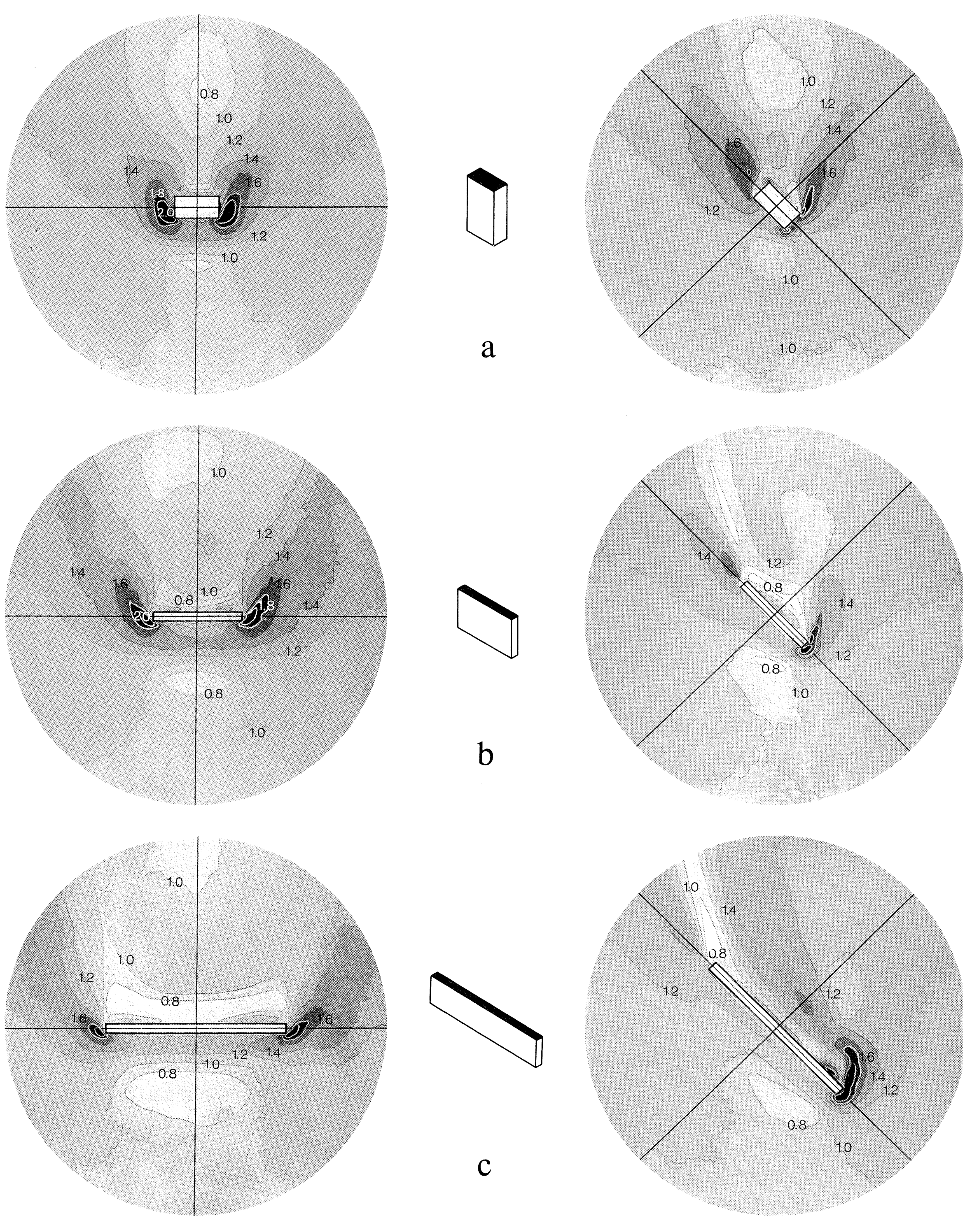


Fig. 15. Influence of height and length of the building, discomfort maps for $\varphi = 0°$ and $\varphi = 45°$.
a. Tower block $b \times l \times h = 20\ \text{m} \times 40\ \text{m} \times 70\ \text{m}$.
b. "High" slab block $b \times l \times h = 10\ \text{m} \times 80\ \text{m} \times 50\ \text{m}$.
c. "Long" slab block $b \times l \times h = 10\ \text{m} \times 160\ \text{m} \times 35\ \text{m}$.

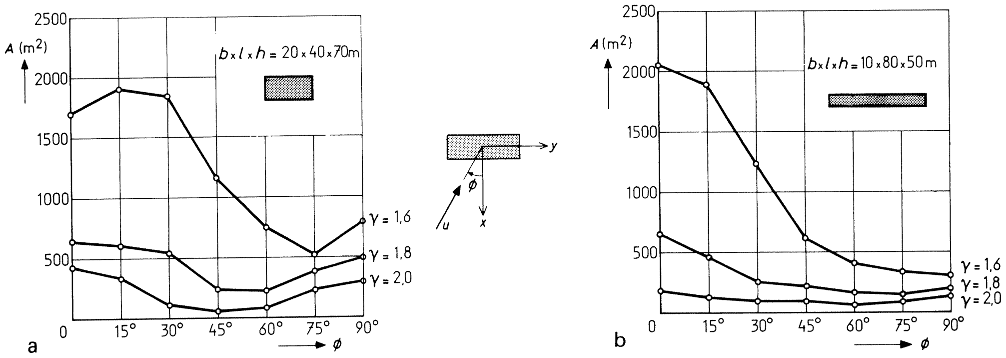


Fig. 16. Size of the area where the discomfort parameter exceeds the values $\gamma = 1.6\text{–}1.8\text{–}2.0$.
a. Building according to Fig. 15a.
b. Building according to Fig. 15b.

6.4 *Rules for the determination of the environment*

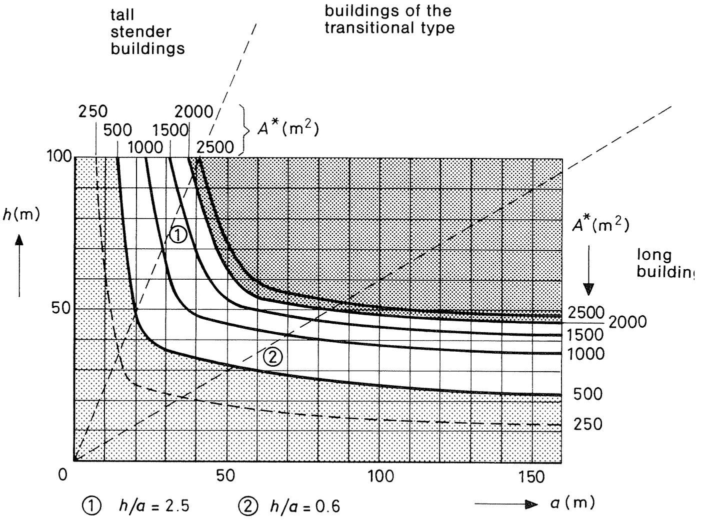
For a large number of buildings the area A^* has been determined for wind parallel to the axes. It follows from the tests that only the dimensions of the windward face of the buildings are of importance. The results are shown in Fig. 17. It is obvious that the area A^* grows very rapidly with increasing height, provided that the length of the building has more or less the same magnitude as the height. In Fig. 17 contour lines are drawn for constant values of A^*. In Fig. 18 these contour lines are projected on the horizontal plan (height versus width of the front face of the building). In this way an excellent insight is obtained into how the environment is influenced by the dimensions of the building.

First of all, three parts may be distinguished. The lower lightly shaded part of the diagram gives dimensions of faces where the discomfort generally will give no problems. Many buildings in Holland have a height between 12 and 14 m. No serious complaints about wind environment around these buildings (and also due to these buildings) are known. For these heights the area $A^* \simeq 250\ \text{m}^2$. So it seemed justified to regard the area $A^* < 500\ \text{m}^2$ as a safe area. If the area is larger than $2000\ \text{m}^2$ the area A^* increases very rapidly with increased height.

For long buildings this means a height of 50 m or more. So if a front of a building is within the heavily shaded area of the diagram, a wind tunnel test if generally recommended. The blank area between the two shaded areas contains all the necessary information to judge the wind environment.

The three regimes of the airflow can also be distinguished in Fig. 18.

a. Tall slender buildings ($h > 2.5$a), Fig. 13a.
   The wind environment is practically independent of increasing height and depends mainly on the length of the windward face of the building.
b. Tall buildings of the transitional type ($2.5\text{a} < h < 0.6\text{a}$), Fig. 13b.
   The wind environment depends both on the length and on the height of the windward face of the building.



▦ windtunnel investigation recommended

☐ environment determinable from the graph.

░ environment satisfactory

Fig. 18. Contour lines for constant values of A^* as a function of the dimensions of the windward face of the building.
a = length (perpendicular to the wind)
h = height

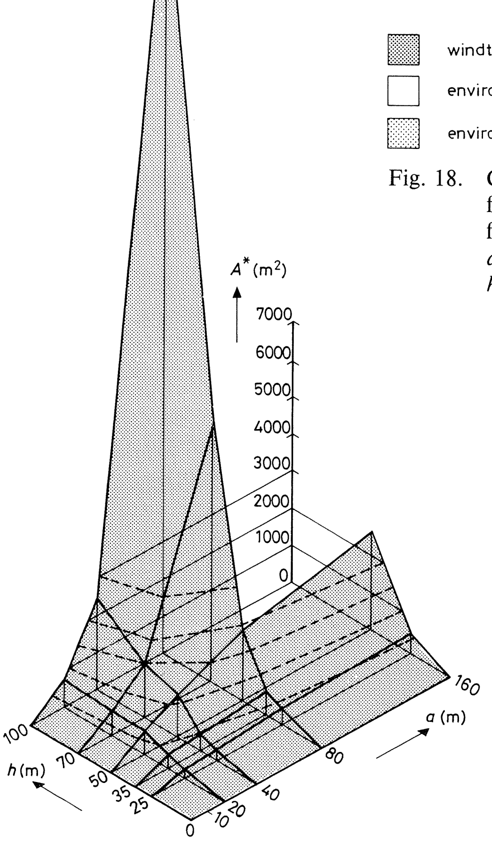


Fig. 17. The area A^* (where $\gamma > 1.6$) as a function of the dimensions of the windward face of the building (a = length, h = height).

c. Long buildings ($h < 0.6a$), Fig. 13c.
The wind environment is mainly dependent on the height of the windward face of the building and practically independent of increasing length.

The boundaries just mentioned give only a rough indication where the airflow has changed from one regime to another, but this is hardly a disadvantage, as more precise information can be obtained from Fig. 18.

6.5 *Rules for the determination of the influence area*

For buildings of the transitional type the influence area can be determined by drawing a circle through the front and rear stagnation points [6, 19] see Fig. 19a. The radius R is practically only dependent on the dimensions of the windward face of the building. The same is valid for the distance e between the centre of the circle and the windward face of the building [16].

$$R = 1.6\sqrt{ah} \tag{2}$$

$$e = 0.9\sqrt{ah} \tag{3}$$

These rules are valid for $1.25 > h/a > 0.33$, see Fig. 20b.

For tall slender buildings the radius R hardly increases with increasing height. So if $h > 1.25a$, a fictitious height $h' = 1.25a$ is substituted in formula (2). The value for e turns out to be somewhat too high, so in this case a smaller coefficient could be chosen, see Fig. 20a.

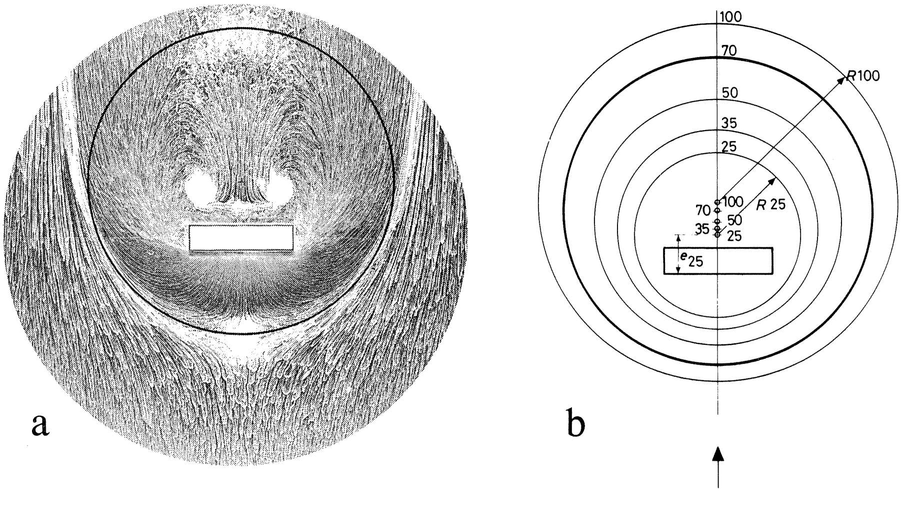


Fig. 19. Determination of the "influence area" by drawing a circle through the front and rear stagnation point.
a. Streamline pattern and influence area for a building with dimensions $b \times l \times h =$ 20 m × 80 m × 70 m.
b. Circles for the influence area for buildings with the same ground plan and a height $h =$ 25-35-50-70-100 m.

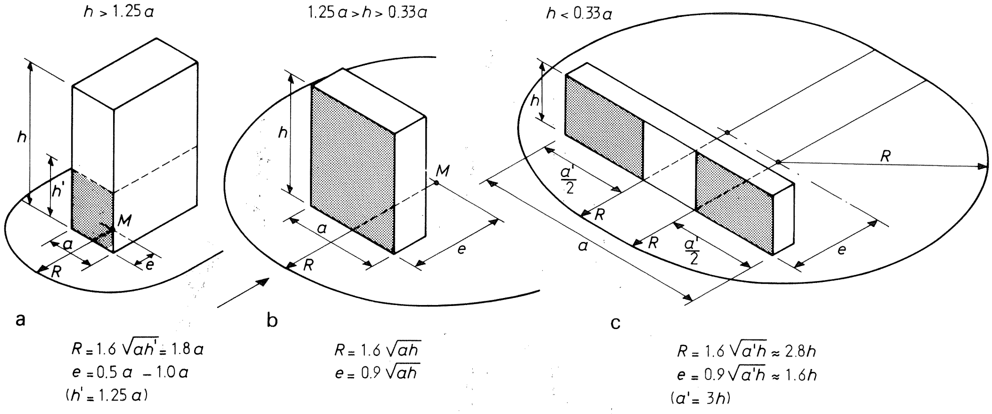


Fig. 20. Determination of the influence area for the three wind regimes, associated with the three main types of single buildings.
a. Tall slender building.
b. High building of the transitional type.
c. Long building.
The effective areas of the front faces of the buildings which have to be taken into account for the determination of R and e are shown shaded.

For long buildings the radius R is practically only dependent on the height of the building and the effect of increasing length can be neglected. So if $a > 3h$, the middle part of the building is neglected and the influence areas are drawn as for two buildings, each with a fictitious length $a' = 3h$, see Fig. 20c.

If the dimensions of the building parallel to the wind are rather large, the influence area has to be adapted to some extent [9]. If the wind is incident under a variable angle with the axes of the building, some indication of the influence area can also be given [19]. It is important to know the influence area around a building for two reasons:

a. If a high building has to be erected in the vicinity of lower buildings, the new building should be so located that the lower buildings are outside the influence area of the new building.
b. If the influence areas of various buildings overlap, there is a possibility of serious interference between the buildings.

The boundaries given for the three wind regimes in Fig. 20 do not coincide with those in Fig. 18. Fig. 21 gives an overview of all the boundaries [19]:

Tall slender buildings

1. $h/a > 2.5$	The discomfort is hardly influenced by a further increase in height of the front face of the building, but only by increasing length.
2. $h/a > 1.25$	The radius R of the influence area is only dependent on the length of the front face of the building.

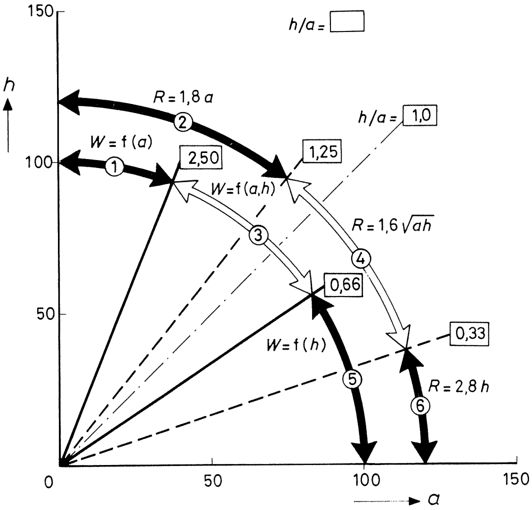


Fig. 21. Effect of the three wind regimes on the discomfort and the size of the influence area.
1-3-5 discomfort
2-4-6 influence area.

Buildings of the transitional type

3. $2.5 > h/a > 0.66$ The discomfort is dependent on the length as well as the height of the front face of the building.
4. $1.25 > h/a > 0.33$ The radius R of the influence area is dependent on the length as well as the height of the front face of the building.

Long buildings

5. $h/a < 0.66 (a > \frac{3}{2}h)$ The discomfort is no longer dependent on increasing length of the building but only on the height.
6. $h/a < 0.33 (a > 3h)$ The radius of the influence area is only dependent on the height of the front face of the building. For wind directions between 30° and 60° there occur “overrolling” vortexes.