WIND ENVIRONMENT AROUND BUILDING CONFIGURATIONS

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 building configurations

1 Introduction

Wind environment around building configurations has been determined using wind discomfort maps and streamline maps.

The results for single buildings, as described in the previous article, will serve as a basis. From the tests it follows that two categories of building configurations can be distinguished:

a. Configurations where the buildings are situated more or less perpendicular to each other. In such cases the wind discomfort can practically always be determined by a kind of superposition of the basic cases valid for the single buildings.
b. Configurations where the buildings are mainly situated parallel to each other. In many of these cases strong transverse air streams will occur, which will cause much greater discomfort then might be expected from the basic cases.

Most phenomena which will occur around building configurations can be described as variations or modifications of the basic air flow patterns around single buildings or simple building configurations.

2 Tests

The following situations have been investigated:

a. Regular configurations of low buildings ($h = 12.5$ m).
b. One high building ($h = 35 - 50 - 70$ m) amidst a regular configuration of low buildings ($h = 12.5$ m).
c. Configurations of high buildings ($h = 25 - 35 - 50 - 70$ m).
d. Single high buildings with building details which may improve or worsen the environment.

For all tests the boundary layer is so chosen that the coefficient for the vertical wind profile is equal to $\alpha = 0.28$. But no precautions have been taken to maintain this value of α over the whole measuring section. So if a regular configuration of low buildings is investigated, the coefficient α will practically remain constant, but when just one single building is present on the measuring section the wind speed at the end of the measuring section will gradually increase, just as in reality.

As stated in [15], after an open space of 400 m × 400 m, the sheltering effect of the buildings will have disappeared, and this is just the size of the measuring section. In all the measuring photographs the wind is blowing from south to north. In the discomfort maps the numbers indicate the magnitude of the discomfort parameter γ (i.e., more or less the magnification factor for the gust speed). The greater the discomfort, the darker the area. The two dark zones which are surrounded by white lines in the discomfort maps have as values for the discomfort parameter: $\gamma = 1.8$ and $\gamma = 2.0$.

3 Low buildings

3.1 *Regular configurations of low buildings*

The most striking feature in these tests is the repetitive character of the discomfort maps for each situation investigated. As soon as the wind has passed one or two basic configurations (i.e., three or four blocks placed together in a certain pattern), the discomfort pattern for each following basic configuration is practically alike, see Fig. 1 [21, 22]. For these low buildings ($h = 12.5$ m) the maximum value of the discomfort parameter is equal to $\gamma = 1.4$ and occurs only over very small areas. Regarding the first column of Fig. 1 where $\gamma = 1.2$, it is quite obvious that blocks perpendicular to the wind have a higher discomfort than blocks parallel to the wind, even though the discomfort is limited (compare Fig. $1a_1$ and $1d_1$). In Fig. $1a_1$ the turbulence in the streets perpendicular to the wind is higher than in the streets parallel to the wind, and the maximum gust speeds in the "perpendicular" streets can reach higher values than in the "parallel" streets. The transverse air streams of Fig. $1a_1$ will increase if the parallel blocks are shifted towards each other, see Fig. $1b_1$. These transverse air streams decrease if the blocks perpendicular to the wind become shorter, see Fig. $1c_1$, and vanish completely if the blocks are parallel to the wind, see Fig. $1d_1$.

The sheltering effect of the configurations can be judged from the third column of Fig. 1 where $\gamma = 0.8$. The long parallel blocks, Fig. $1a_3$ and $1d_3$, do not have any substantial sheltering effect; this effect becomes much higher, however, if the blocks are placed perpendicular to each other, Fig. $1b_3$ and $1c_3$.

Long blocks perpendicular to each other can have increased discomfort for wind at 45°, see Fig. 2a and 2b, where only discomfort maps for $\gamma = 1.0$ are given.

From Fig. $2b_1$, c_1 and c_2 it can be seen that each separate building of a configuration has a very limited influence on the environment some distance away from that building.

In front of a single building reverse air streams will occur over a rather small zone; in Fig. $2b_1$ all the buildings perpendicular to the wind practically act as single buildings. The same is valid for Fig. $2c_2$, if the buildings in row 1, 2 and 4 are regarded. But the buildings in row 3 act in the same way as all the buildings in Fig. $2c_1$. Here transverse air streams will occur over a much wider zone, and the occurrence of these air streams in Fig. $2c_2$ is only due to the fact that there exists a small irregularity in the comb-shaped pattern.

The test results in summary are:

a. Regular configurations of low buildings give a repetitive discomfort pattern as soon as the wind has passed one or two basic configurations.
b. An increasing density of the built-up area will give a decreasing discomfort.
c. There is a maximum of discomfort if the wind is blowing perpendicular to the length of parallel long buildings. These configurations are very sensitive to transverse air streams.
d. The transverse air streams can be reduced by increasing the distance between the parallel long blocks and by placing perpendicular blocks in between the parallel rows.

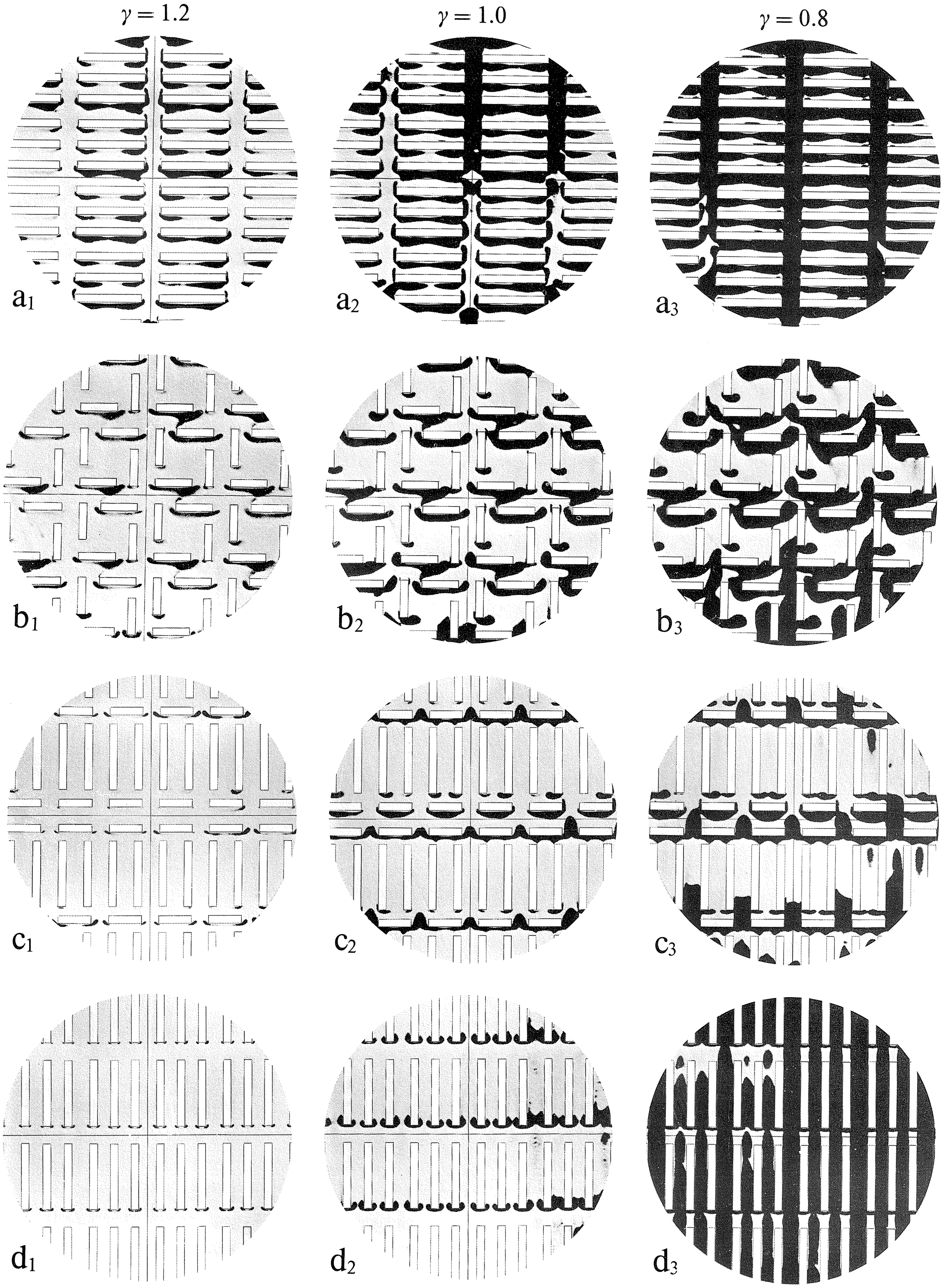


Fig. 1. Regular configurations of medium-high buildings ($h = 12.5$ m). Wind discomfort maps for $\gamma = 1.2–1.0–0.8$. Street width $s = 20$ m.

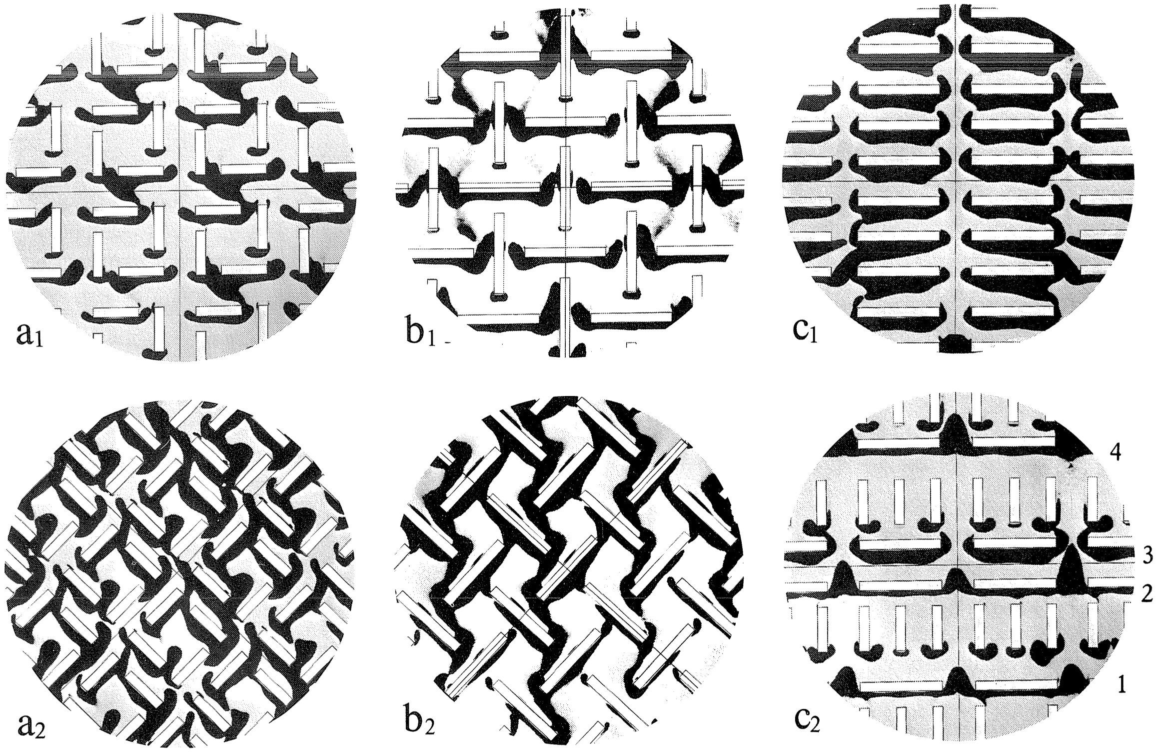


Fig. 2. Comparison of the wind discomfort pattern in front of some building configurations and influence of wind direction for two configurations. Wind discomfort maps for $\gamma = 1.0$.

e. There is a minimum of discomfort and minimum shelter if the wind is blowing parallel to the length of the blocks.
f. Configurations where the blocks are alternately placed perpendicular to each other cause increased discomfort for wind at 45° with respect to the axes of the blocks.

3.2 *One high building amidst a regular configuration of lower buildings*

In all the tests the situation has been compared when a high building stands alone and when it is surrounded by lower buildings. In Fig. 3 an example of such a situation is given. The main results of the tests are:
a. The maximum discomfort in the immediate vicinity of the high building is mainly determined by the dimensions of that building alone.
b. The sheltering effect of the lower buildings is especially felt some distance away from the high building.
c. The sheltering effect of the lower buildings increases if the difference in height between the high building and the lower buildings decreases. In the difference in height is 40 m or more, the sheltering effect of the lower buildings is small. But if the difference in height is 20 m or less, even the size of the areas with maximum discomfort around the high building is decreased.

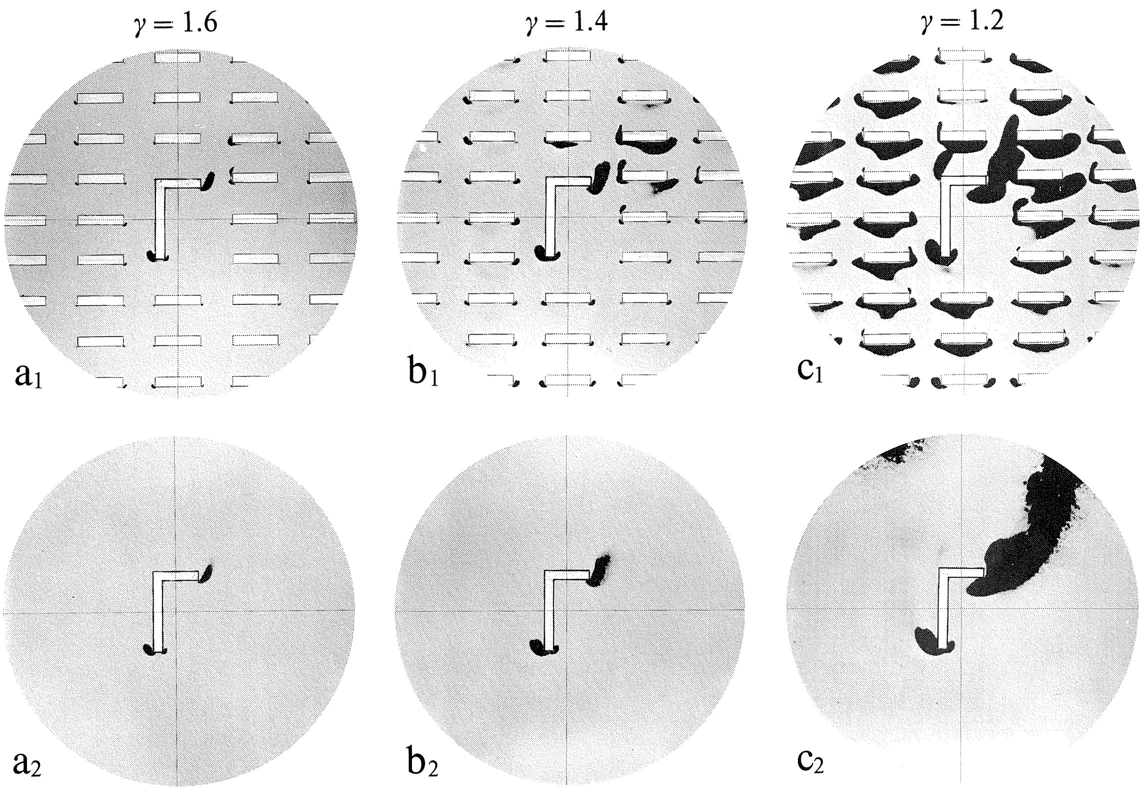


Fig. 3. Wind discomfort maps for a high building alone 10 m × (45–80 m) × 50 m and the same building surrounded by a regular configuration of lower buildings ($h = 12.5$ m). Wind discomfort maps for $\gamma = 1.6–1.4–1.2$.

d. Lower buildings, with their long axis perpendicular to the wind, situated in front of a higher building may cause some increased discomfort in front of the high building.

4 General remarks about interaction

The influence area around a single rectangular building can be determined by means of the formulas:

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

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

with some small modifications for tall slender buildings and long buildings, as shown in the previous article, Chapter 6.5. If the buildings are completely outside each other's influence area, there will be no interaction, and streamline maps and discomfort patterns may always be superimposed.

So if there is a configuration of parallel rows of long buildings, there will be no interaction if the distance between the rows is larger than 5 times the height of the buildings ($s > 5h$). Even if the influence areas do overlap, but one building is outside the influence area of the other building, interaction remains slight, see Fig. 4. This means for tall

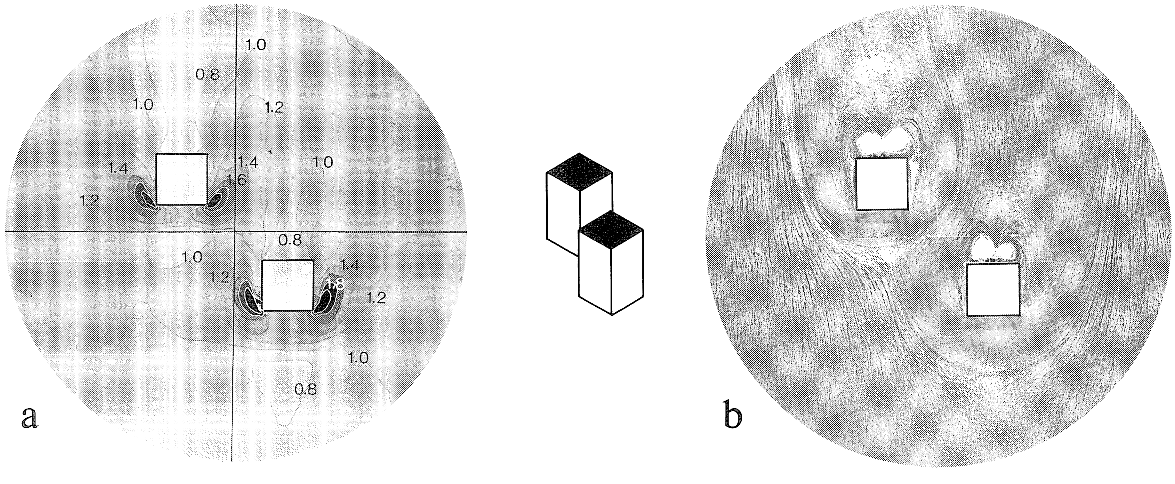


Fig. 4. Wind discomfort map and streamline pattern for two high buildings ($b \times l \times h =$ 40 m × 40 m × 70 m) with weak interaction (distance between the buildings $t_x = t_y =$ 40 m).

slender buildings a distance greater than $3a$ and for long buildings a distance greater than $3h$. But there are a good many configurations where the interaction remains small, even if the buildings are inside each others influence areas. This is so for a row of buildings in one line and for buildings situated perpendicular to each other. In Fig. 5 two examples are given, one for a composite building and one for a similar building configuration. In Fig. 5a the discomfort maps are given for a high building of the transitional type, with wind parallel to the long axis (Fig. $5a_1$) and wind perpendicular to the long axis (Fig. $5a_2$) These two discomfort maps should be compared with the discomfort map in Fig. $5b_1$ for a composite building consisting of these two basic units.

At the corresponding points the same discomfort pattern is found, with the exception of the connection between the two units where the wind is prevented from passing. In Fig. $5b_2$ a configuration of these two buildings is given, a short distance apart, and now the patterns are even more alike.

This means that a certain kind of superposition can be used to determine the wind environment of composite buildings and building configurations, so long as the wind environment - given in discomfort maps - is known for the comparable single buildings of simple shape. The (transparent) discomfort maps are merely superimposed, and at the most affected spots the maximum areas are taken into account where the discomfort parameter exceeds certain values; compare Fig. $5a_1$, a_2 and b_1.

The reason for this possibility is clarified on considering Fig. 6. In Fig. 6a the discomfort map and the streamline pattern are given for the same building as in Fig. 5a, but now for wind incident at 45° with respect to the axes. In Fig. 6b these patterns are given for the samen building configuration of Fig. $5b_2$, but now also for wind incident at 45°.

Considering the streamline patterns for the single building in Fig. $6a_2$ and the building configuration in Fig. $6b_2$, it will be obvious that the air stream for the two single buildings needs only to be changed in a minor way to "fit" into the streamline pattern for the building configuration. This is especially so if the buildings are alternately perpen-

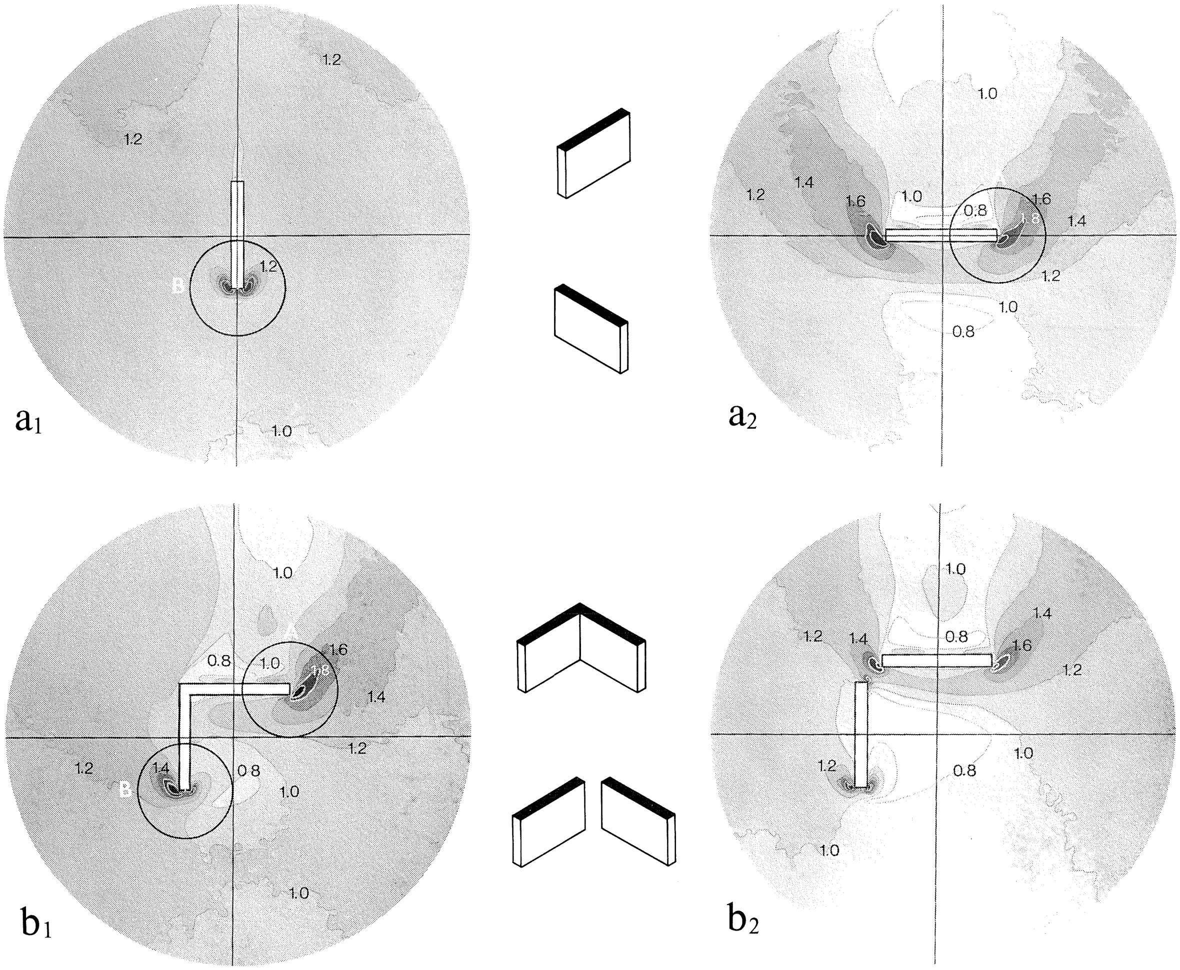
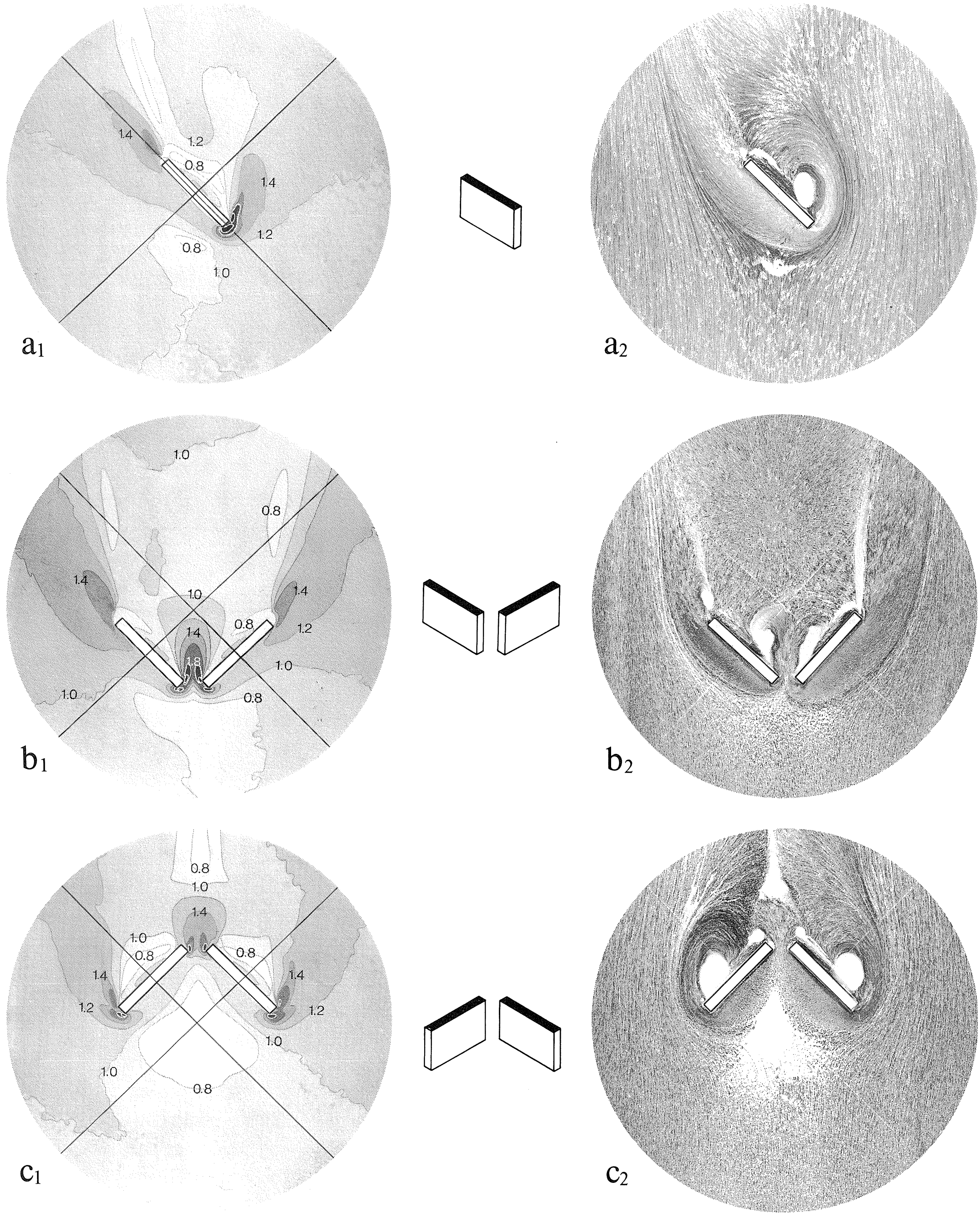


Fig. 5. Comparison of the wind discomfort maps of a single high slab block ($b \times l \times h = 10$ m $\times$ 80 m $\times$ 50 m) with wind parallel and perpendicular to the long face and a building composed of these two blocks (b_1) and a building configuration of these two blocks (b_2; $u = 14$ m).

dicular to each other and it remains so for all wind directions. In Fig. 6b the two buildings are situated in a "wind spreading" shape, whereas in Fig. 6c the buildings are situated in a "wind catching" shape. And even here the same kind of discomfort pattern will occur and the so called "venturi effect" will hardly play any role. The wind discomfort between the two buildings seems even less severe than for the "wind spreading" shape. From the discomfort map and streamline pattern of Fig. 6c it also appears that in front of the two buildings a large zone with decreased wind speed occurs, so that most of the wind does not blow through the opening, but over the two buildings. Nevertheless the building configuration may be less appreciated than the single building, as passing between the two buildings is always unpleasant because of the high wind speed in the opening, whereas with the single building this location can more easily be avoided.


1.4
1.2
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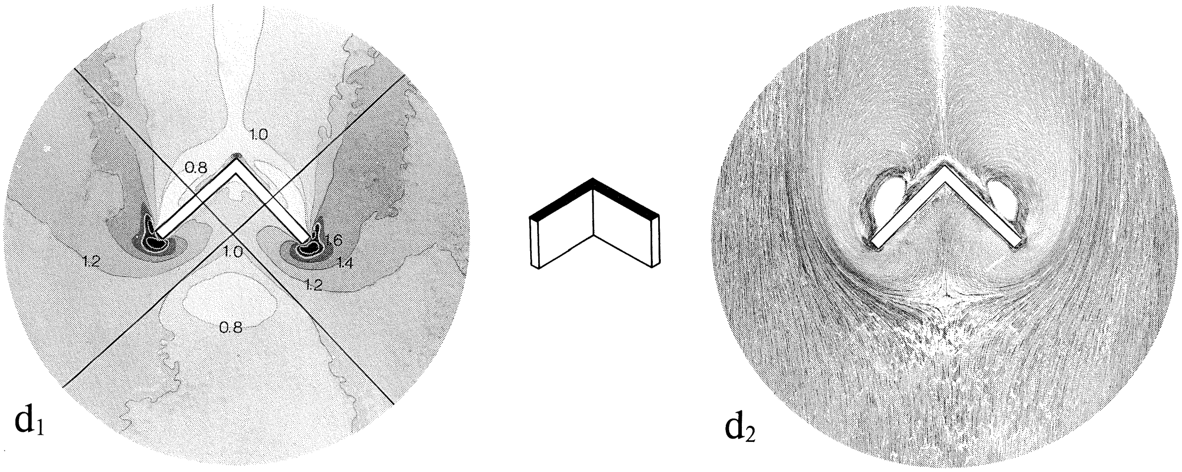


Fig. 6. Similarity between the wind discomfort map and the streamline pattern for the following cases:
a_1–a_2. a single building
b_1–b_2. a building configuration in a "wind spreading" layout
c_1–c_2. a building configuration in a "wind catching" layout
d_1–d_2. a composite building in a "wind catching" layout

In Fig. 6d, finally, the composite building of the same shape is shown. Again there is the same kind of disturbance at the two outer corners of the building and obviously no disturbance at all at the connection of the two parts, as now the whole air stream in front of the building has to pass over the building and on both sides of it.

It is easily seen that two buildings close together will act more or less as one building with regard to the "overall" behaviour of the wind, and that concentrated air streams will occur only in the direct vicinity of the opening.

5 Openings between and under buildings

As mentioned in 4, there will be no interaction between two buildings if their influence areas do not overlap. This means $t > 2.5$ a for tall slender buildings and $t > 2.5h$ for long buildings.

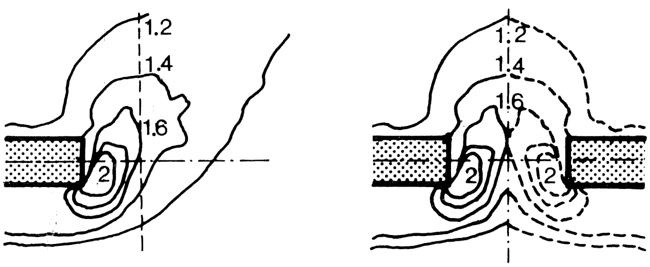


Fig. 7. Superposition of wind discomfort maps:
a. Discomfort map for the corner of a building.
b. Maps of two adjacent corners superimposed; each map is valid between the building to which it relates and the line of symmetry.

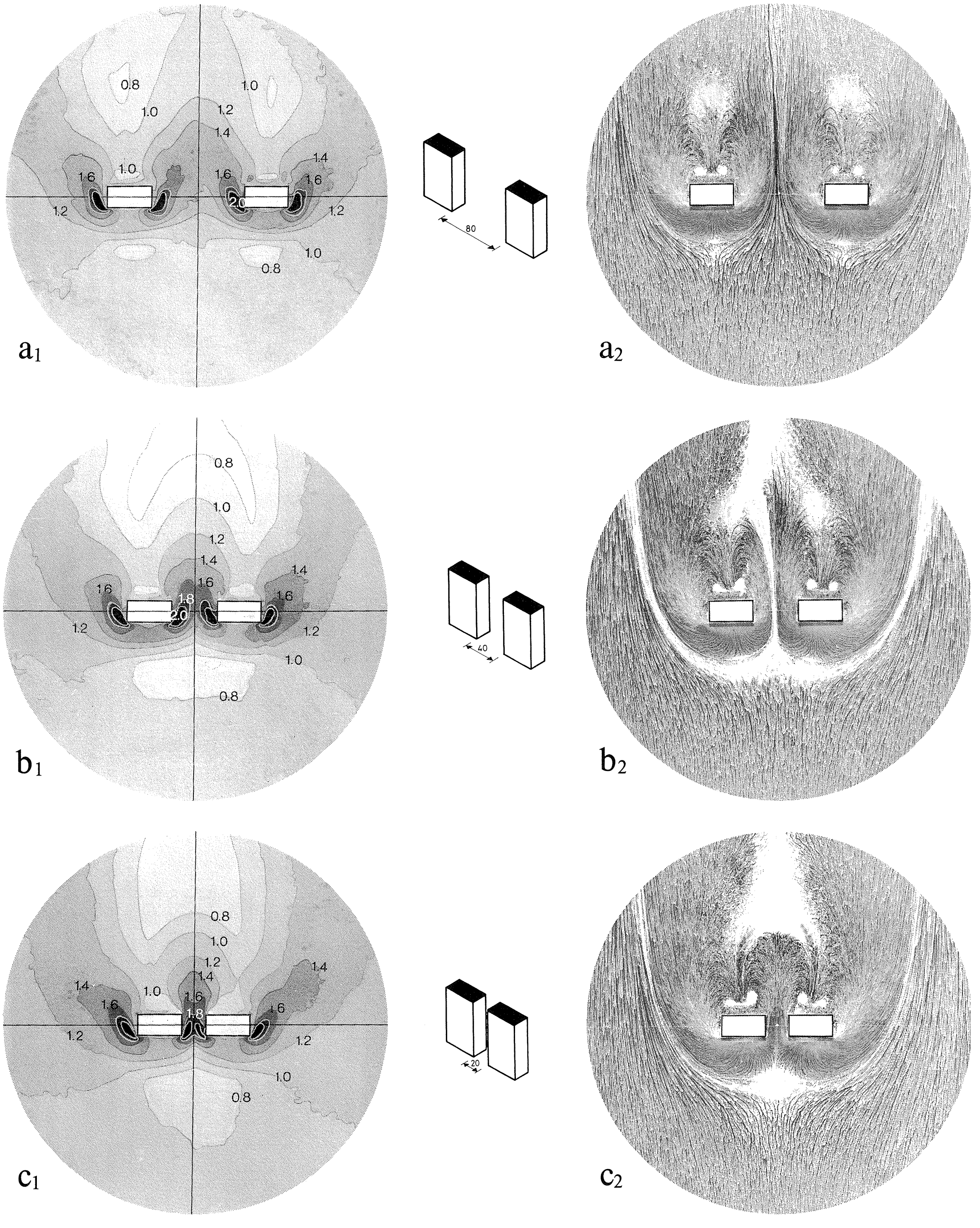


Fig. 8. Influence of a varying distance between two tower blocks in one line ($b \times l \times h = 20$ m × 40 m × 70 m)
a. distance $t = 80$ m
b. distance $t = 40$ m
c. distance $t = 20$ m

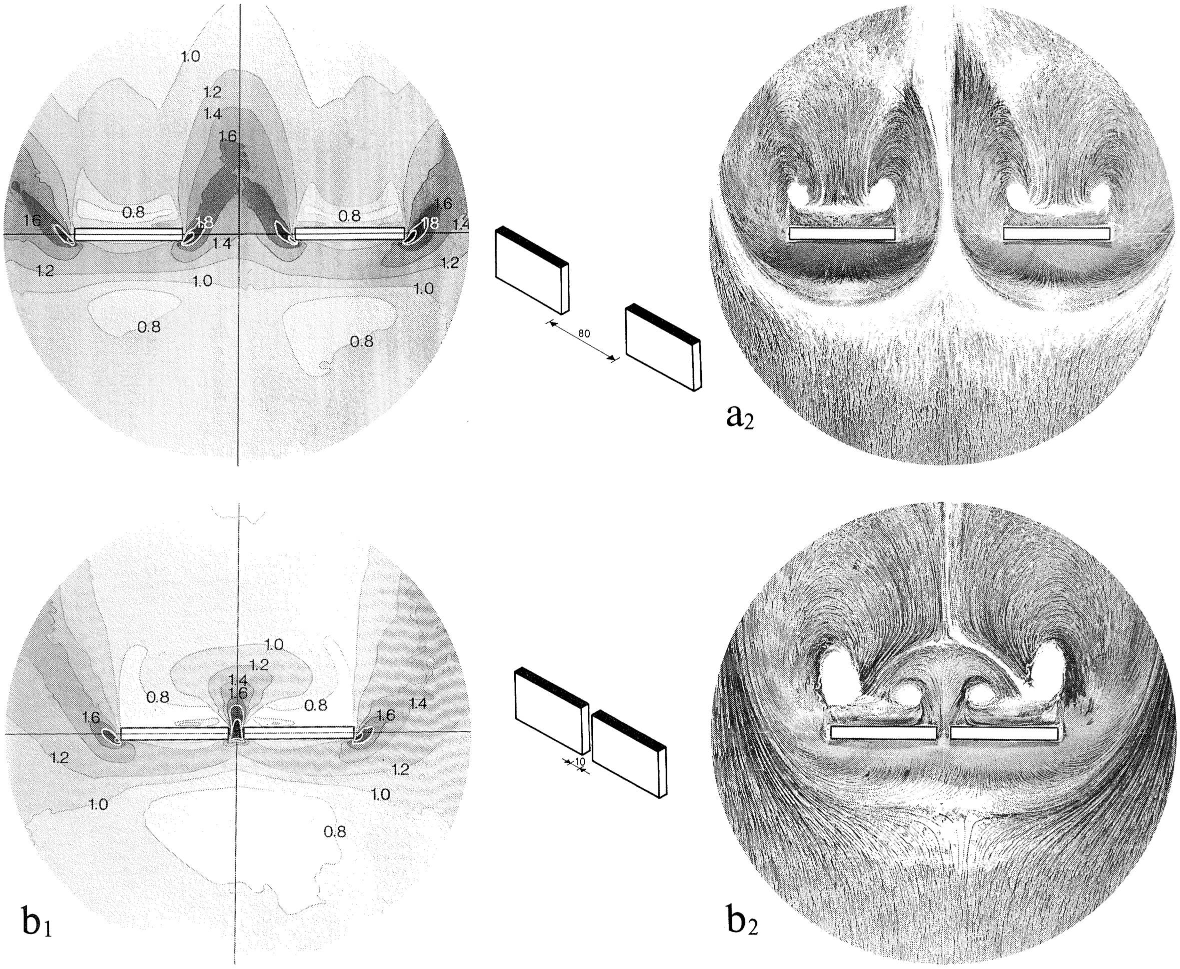


Fig. 9. Influence of the distance between two slab blocks ($b \times l \times h = 10$ m $\times$ 80 m $\times$ 50 m)
a. distance $t = 80$ m
b. distance $t = 10$ m

If the rule of superposition can be used, there will be some interaction if the influence areas of the two buildings do overlap, and there will be stronger interaction if one building is within the influence area of the other building. The effects on discomfort, however, remain limited. The direction of some air streams may undergo some change, and also the discomfort areas may change a little, but as an overall picture the discomfort patterns of the two single buildings can be superimposed as shown in Fig. 7. The two buildings - with their respective discomfort maps - are shifted closer together to obtain a new discomfort map for the combination of the two. For reasons of symmetry just that part of the discomfort map is valid which extends from each building to the (new) line of symmetry. In Fig. 8a the buildings hardly influence each other. In Fig. 8c the gap between the buildings is so small that the streamline pattern already resembles more or less the pattern for one single building. In Fig. 9 the situation is shown for two high buildings of the transitional type. In Fig. 9a there is seen to be hardly any interaction,

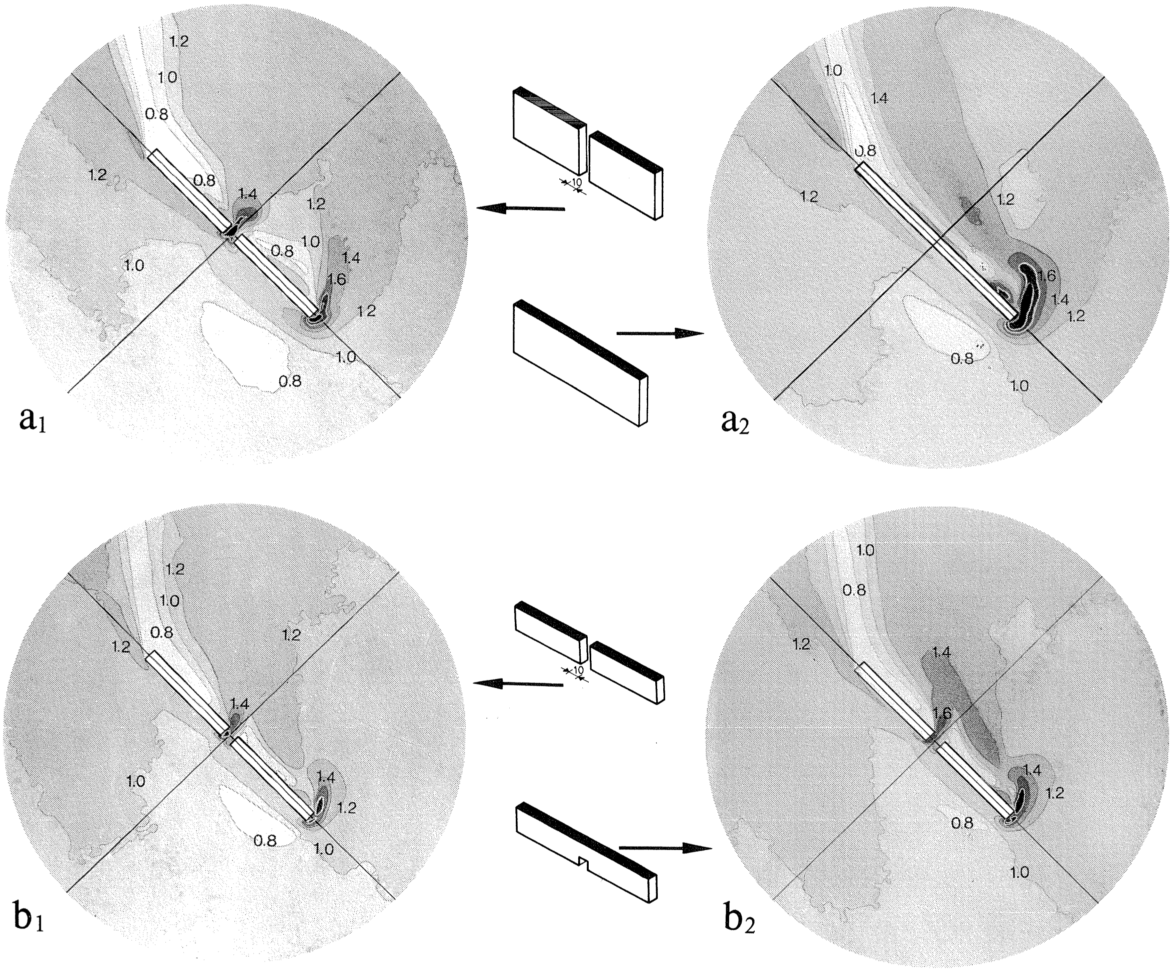


Fig. 10. Wind incident at 45°
a_1. two buildings ($b \times l \times h = 10$ m $\times$ 80 m $\times$ 50 m; $t = 10$ m)
a_2. one building ($b \times l \times h = 10$ m $\times$ 160 m $\times$ 35 m)
b_1. two buildings ($b \times l \times h = 10$ m $\times$ 80 m $\times$ 35 m; $t = 10$ m)
b_2. one building with an opening ($b \times l \times h = 10$ m $\times$ 160 m $\times$ 25 m; opening $l_0 \times h_0 = 10 \times 10$ m).

whereas in Fig. 9b the opening between the buildings is so small that the affected area between the buildings is greatly reduced. From the streamline pattern in Fig. 9b_2 it is also apparent that the two buildings begin to act as one "long" building. Now, if two buildings close together act more or less as one building of similar shape, the pressure differences between the windward and the leeward faces of the building will also be more or less the same, which means that the wind speed in the opening must be independent of the width of the opening. On the other hand, the affected area will then be more or less proportional to the width of the opening. The same considerations apply if the buildings are perpendicular to each other with a small opening between them, as in Fig. 6.

For long buildings ($1 > 3h$) an "overrolling" vortex will develop if the wind is incident at an angle between 30° and 60°, with a maximum effect for $\varphi = 45°$. But this effect only occurs if each single building can be regarded as a long building, see Fig. 10. In Fig. $10a_1$ two high buildings of the transitional type with a small opening between them do not develop the overrolling vortex, even though the total length of the two buildings is more than 160 m, whereas the height is 50 m. At the windward corner of the secone building more or less the same phenomena occur as at the windward corner of the first building. In Fig. $10a_2$ one single building with a length of 160 m and a height of 35 m is shown, and now the overrolling vortex is clearly visible. In Fig. $10b_1$ the height of the two buildings is 25 m, so each building can be regarded as a long building.

The overrolling vortex is apparent particular at the first building, though less pronounced than in Fig. $10a_2$ because of the reduced height and length. In Fig. $10b_2$ one long building with a length of 160 m and a height of 25 m is shown ($l/h = 6.4$), but now with an opening under the building. In this case the overrolling vortex is more strongly developed, whereas the discomfort in the opening is practically the same as in the case of Fig. $10b_1$, as might be expected.

Some buildings are raised above the ground over the main area of the building and are only locally supported by columns, parallel (shear) walls and concrete cores.

In Fig. 11a the building is of the usual type, in Fig. 11b there is only a rigid core at the centre of the building, and in Fig. 11c there are two rigid cores, each at the far end of the building. In both cases columns or shear walls were omitted in the tests. In Fig. 11b the downward air stream in front of the building will now be transported to a great extent underneath it and much less at the corners of the building. In front of the building the discomfort is greatly decreased, but under and behind it the discomfort is greatly increased. Nevertheless is the streamline pattern in front of the building in Fig. $11b_2$ almost the same as in Fig. $11a_2$.

Practically from the front face of the building the usual reverse air streams also occur in Fig. $11b_2$, and the influence areas in the two diagrams are also the same.

In Fig. 11c the rigid cores are at the two ends of the building and this is more or less a situation of a building with a very wide opening under it. Again concentrated air streams under and behind the building will occur, as well as increased corner streams, with a smaller affected area than in Fig. $11a_1$. Obviously, open spaces under buildings are not suitable for any kind of social activity.

The influence of columns or supporting walls is shown in Fig. 12, where for the sake of clarity the rigid cores have been omitted in order to separate the effect of the two influences. Parallel walls will produce more concentrated air streams than rows of columns, especially for wind incident at 45°.

6 Configurations of four buildings in mutually perpendicular arrangement

When configurations of four buildings are regarded, the situation becomes more complicated and the interaction increases.

In Fig. 13a and c two buildings in an "open V-shape" are shown, in the "wind catching" and in the "wind spreading" layout respectively.

In the asymmetrical case the air streams are strongly directed by the shape of the

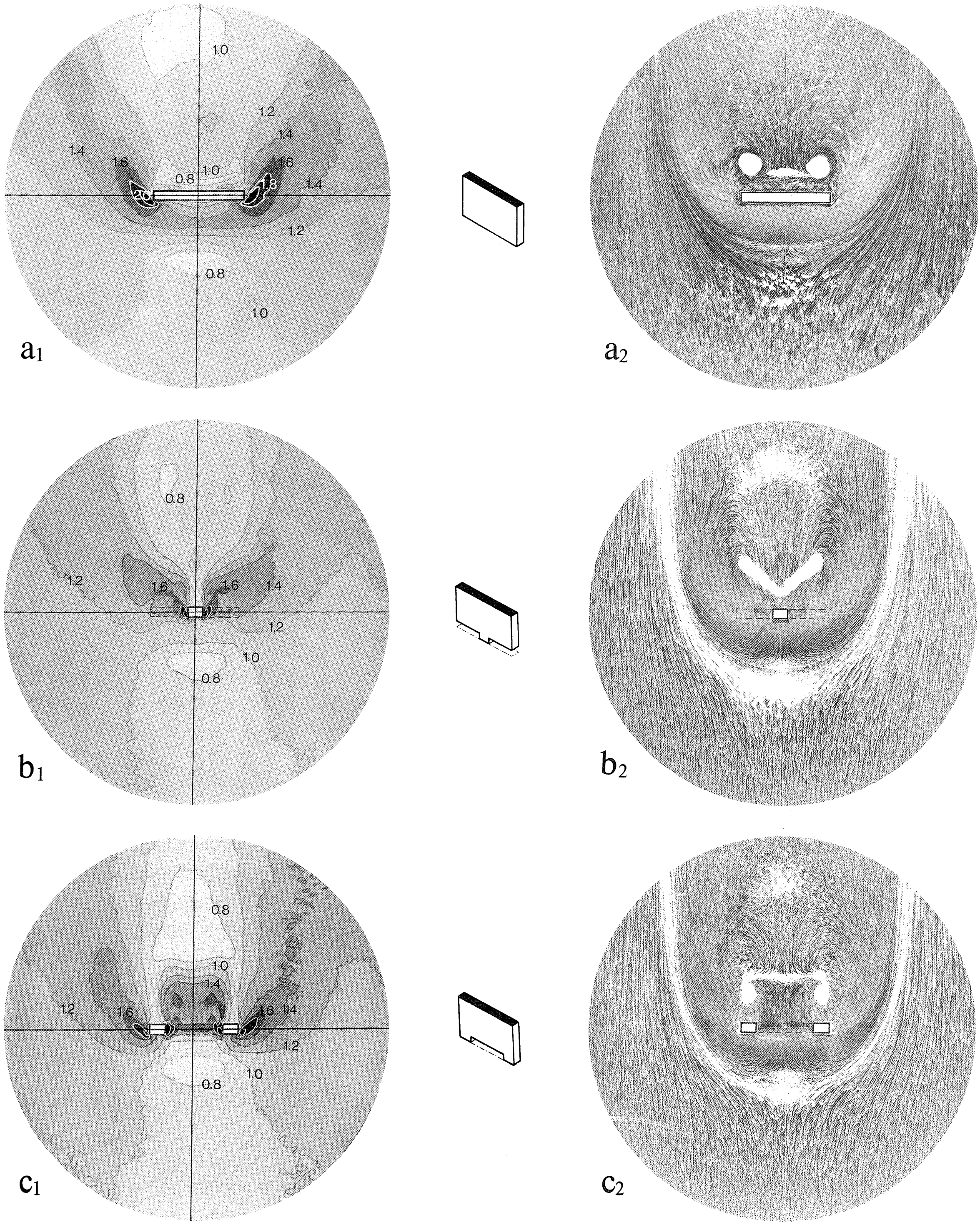


Fig. 11. Influence of open spaces under buildings
a. traditional building ($b \times l \times h = 10$ m $\times$ 80 m $\times$ 50 m)
b. core in the middle of the building
c. one core at each end of the building.

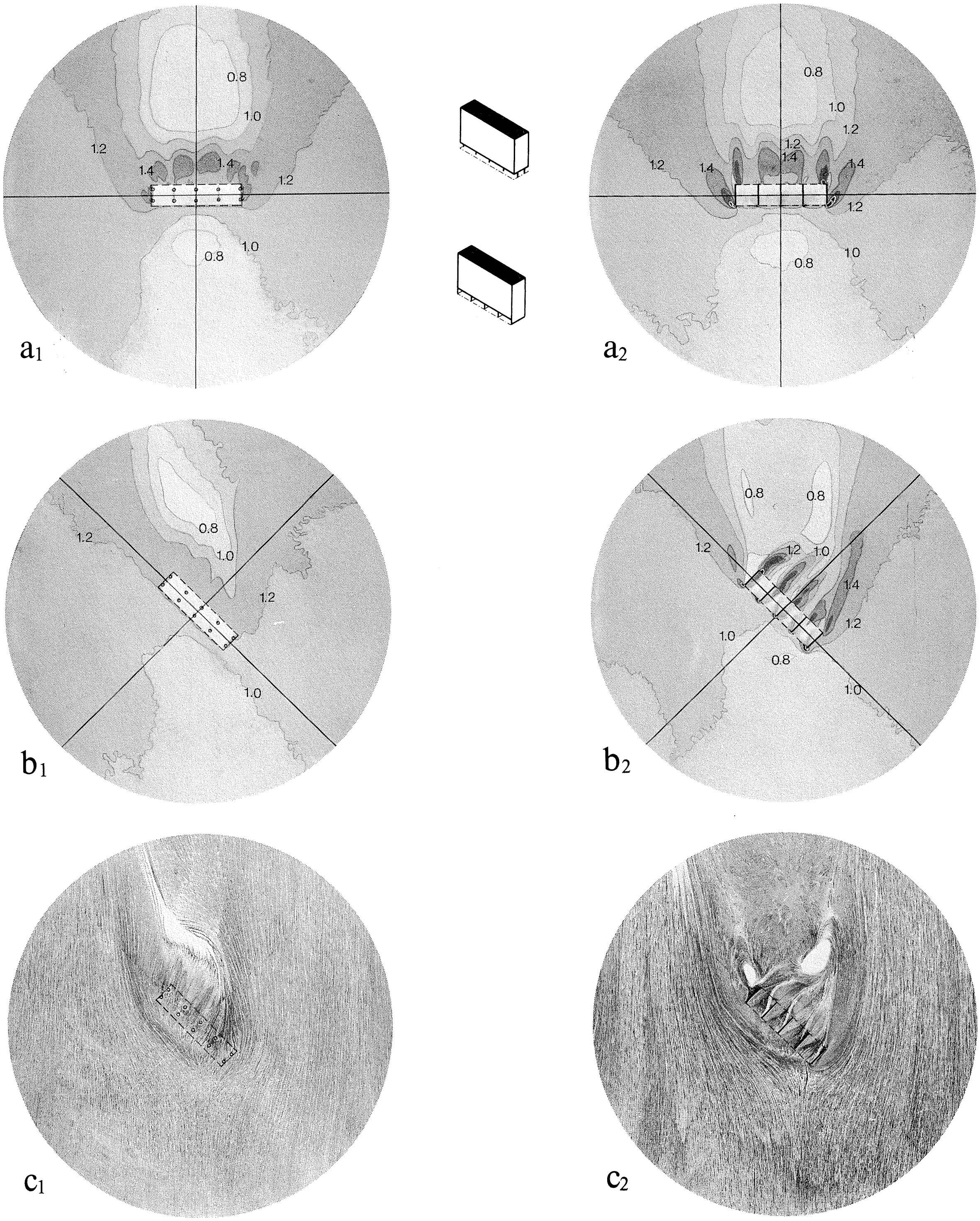


Fig. 12. Open space under buildings, influence of the mode of supporting ($b \times l \times h = 20\ \text{m} \times 80\ \text{m} \times 50\ \text{m}$) cores omitted

a_1–c_1. building supported by columns

a_2–c_2. building supported by shear walls.

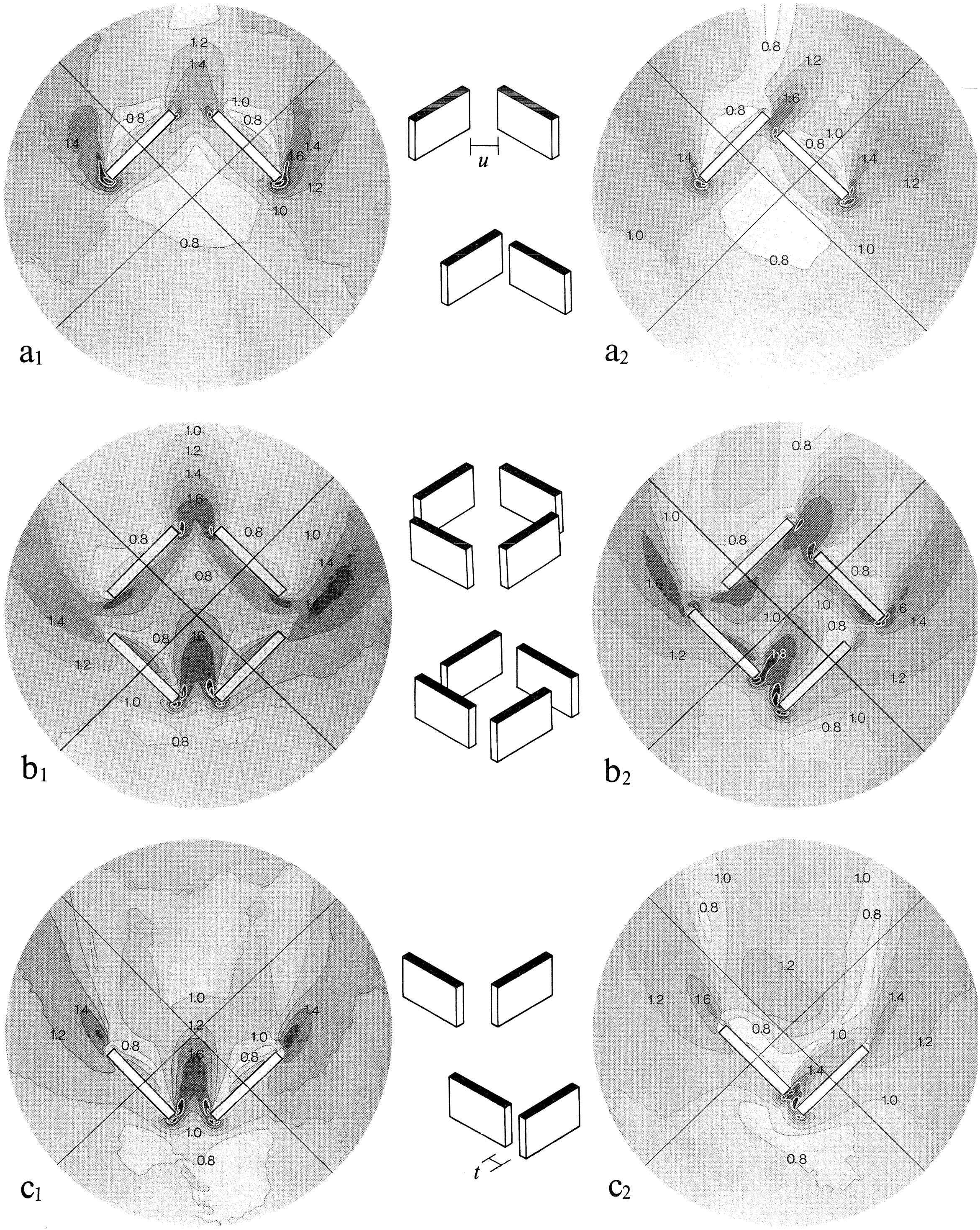


Fig. 13. Building configurations of four buildings compared with two configurations of two buildings

a_1–c_1. symmetrical building configuration of two buildings in a “wind catching” and “wind spreading” layout ($b \times l \times h = 10$ m $\times$ 80 m $\times$ 50 m; $u = 28$ m)

a_2–c_2. asymmetrical building configuration of two buildings in a “wind catching” and “wind spreading” layout ($b \times l \times h = 10$ m $\times$ 80 m $\times$ 50 m; $t = 20$ m)

b_1. symmetrical configuration of four buildings ($b \times l \times h = 10$ m $\times$ 80 m $\times$ 50 m; $u = 28$ m)

b_2. asymmetrical configuration of four buildings ($b \times l \times h = 10$ m $\times$ 80 m $\times$ 50 m; $t = 30$ m)

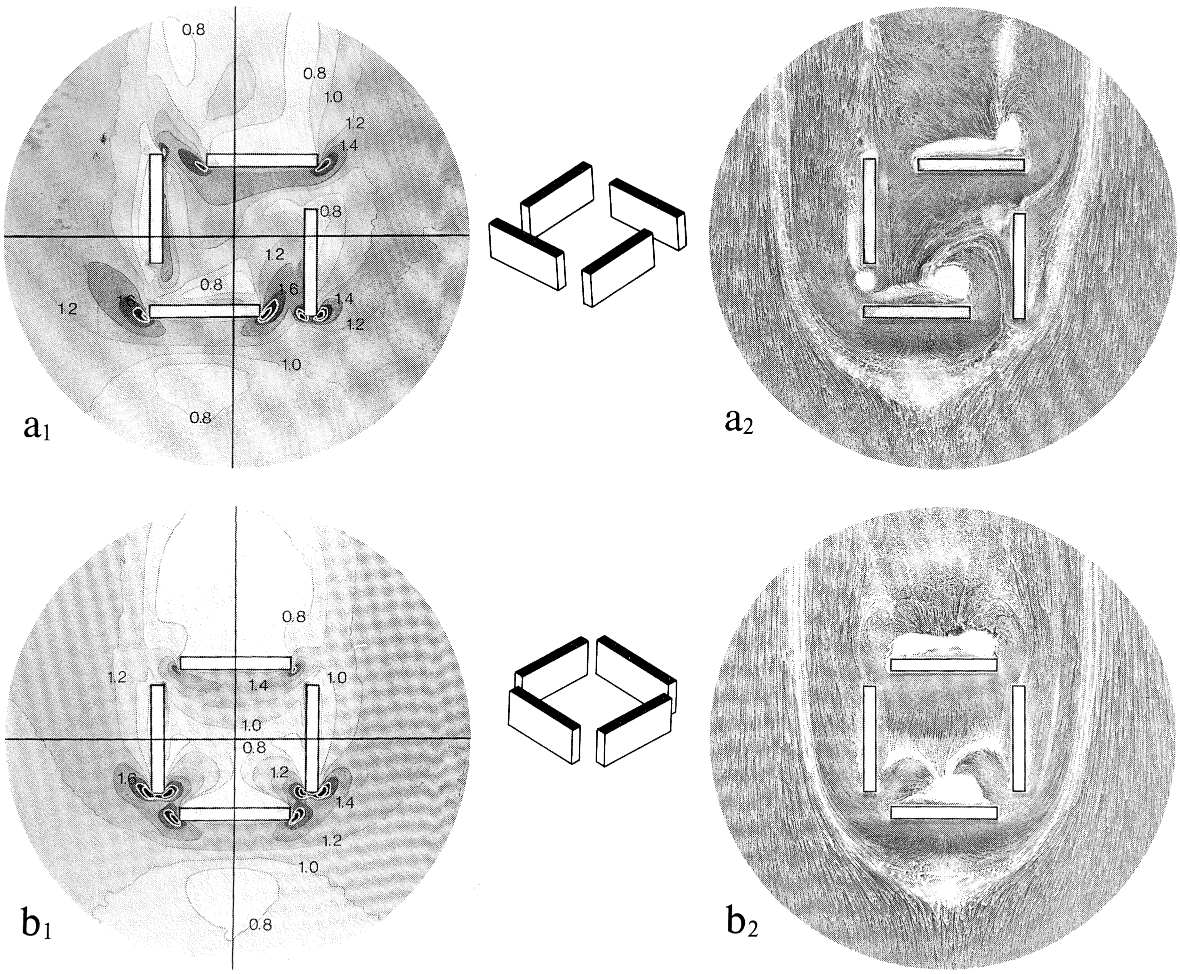
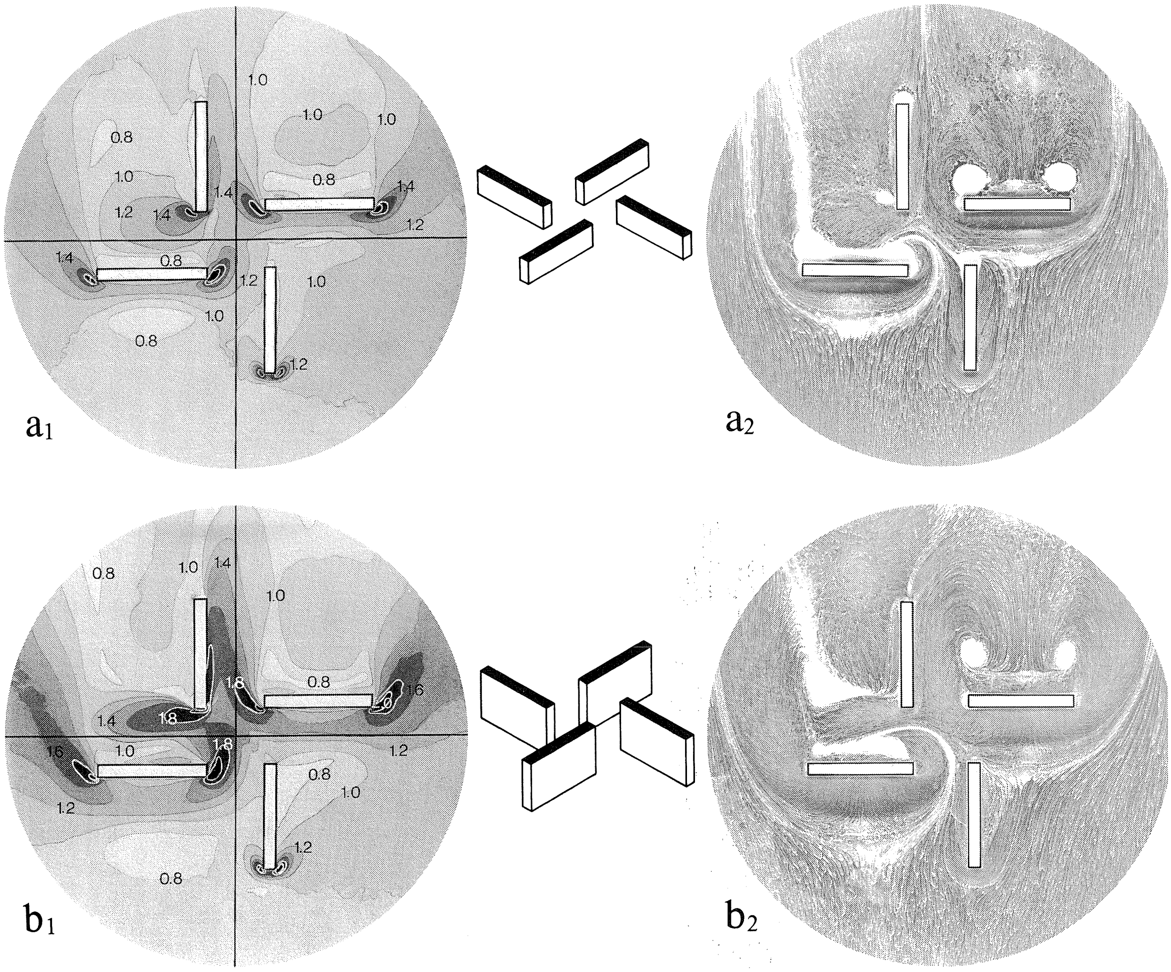


Fig. 14. Building configuration of four buildings in the shape of an open courtyard, with wind parallcl to the axes of the buildings
a. asymmetrical shape ($b \times l \times h = 10$ m $\times$ 80 m $\times$ 35 m; $t = 30$ m)
b. symmetrical shape ($b \times l \times h = 10$ m $\times$ 80 m $\times$ 35 m; $u = 14$ m).

opening (Fig. 13a_2 and c_2). Fig. 13b_1 shows the configuration of four buildings in the shape of an "open courtyard" which can be regarded as the superposition of Fig. 13a_1 and c_1. The pattern in front of the first two buildings in the "wind spreading" layout is quite similar.

Midway in the building configuration the discomfort outside the courtyard is increased due to the presence of the second pair of buildings. But for the two buildings in the "wind catching" layout the situation changes. The front corner streams are almost eliminated by the guiding effect of the other two buildings, and the discomfort in the courtyard in front of the two "wind catching" buildings is increased by the downward air streams of the two "wind spreading" buildings.

The discomfort on the windward side of the second pair of buildings is also increased as compared with Fig. 13a_1. In Fig. 13b_2 the open courtyard is no longer symmetrical and



the air streams are rather strongly directed towards the openings. Fig. 13b_2 cannot fully be regarded as a superposition of Fig. 13a_2 and c_2, as the distance between the buildings is different. The trend of the phenomena is clearly visible, however. In Fig. 14 the situation is shown where the wind is incident parallel and perpendicular to the same configurations, but now the height of the building is $h = 35$ m. The wind environment in the symmetrical case seems more preferable then in the asymmetrical case.

If configurations in the shape of a windmill are considered, the interaction between the buildings becomes even stronger, mainly due to the fact that the buildings are so near together at the centre of the configuration. In Fig. 15 discomfort maps and streamline patterns are shown for such configurations with a height of 25 m and 50 m.

At a first glance both patterns are more or less alike for a height of 25 m and 50 m, but especially for wind incident at 45° the precise location of the most affected areas can change considerably for the low and the high building configuration. And that in particular is the reason why full field information is so important. If merely a few measuring points are applied in a wind tunnel test, one may get the impression that the situation

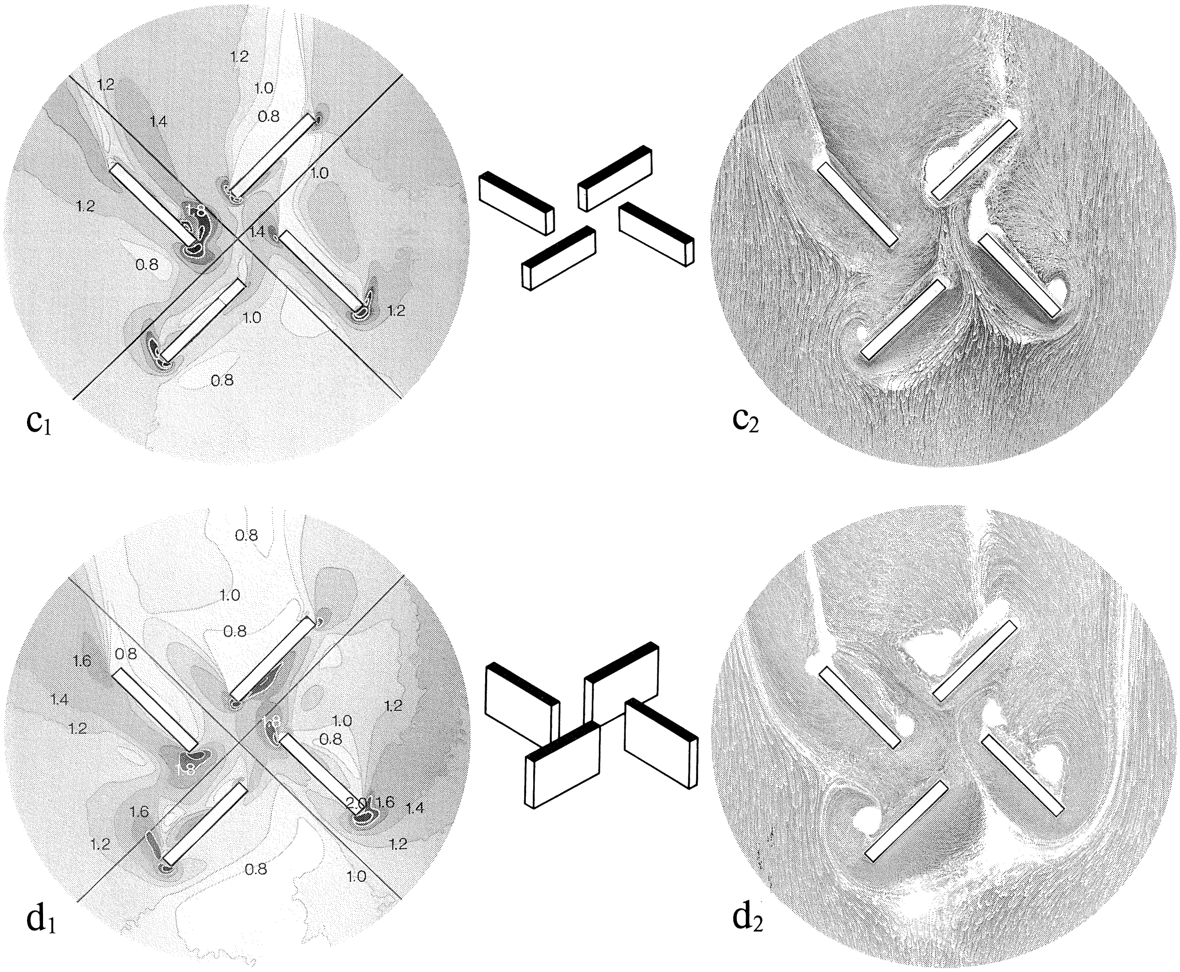


Fig. 15. Configuration of four buildings in the shape of a windmill
a–c. $b \times l \times h = 10$ m $\times$ 80 m $\times$ 25 m; $t = 40$ m
b–d. $b \times l \times h = 10$ m $\times$ 80 m $\times$ 50 m; $t = 40$ m.

has considerably improved at a certain point, without being aware that at a closely adjacent point – where no measuring instrument was applied – the situation may have worsened. The environment is determined by the wind behaviour over the whole area and can only be judged by inspecting the whole area. In our opinion this is the reason why certain aspects of the air stream in wind tunnel tests of building configurations are over- and underestimated or even overlooked.

7 Configurations of parallel buildings

In the proceeding chapters configurations of buildings have been treated for which the principle of superposition remains more or less valid. If the discomfort pattern for one building is known, the pattern for a configuration of two or four buildings or for a composite building can be estimated reasonably well.

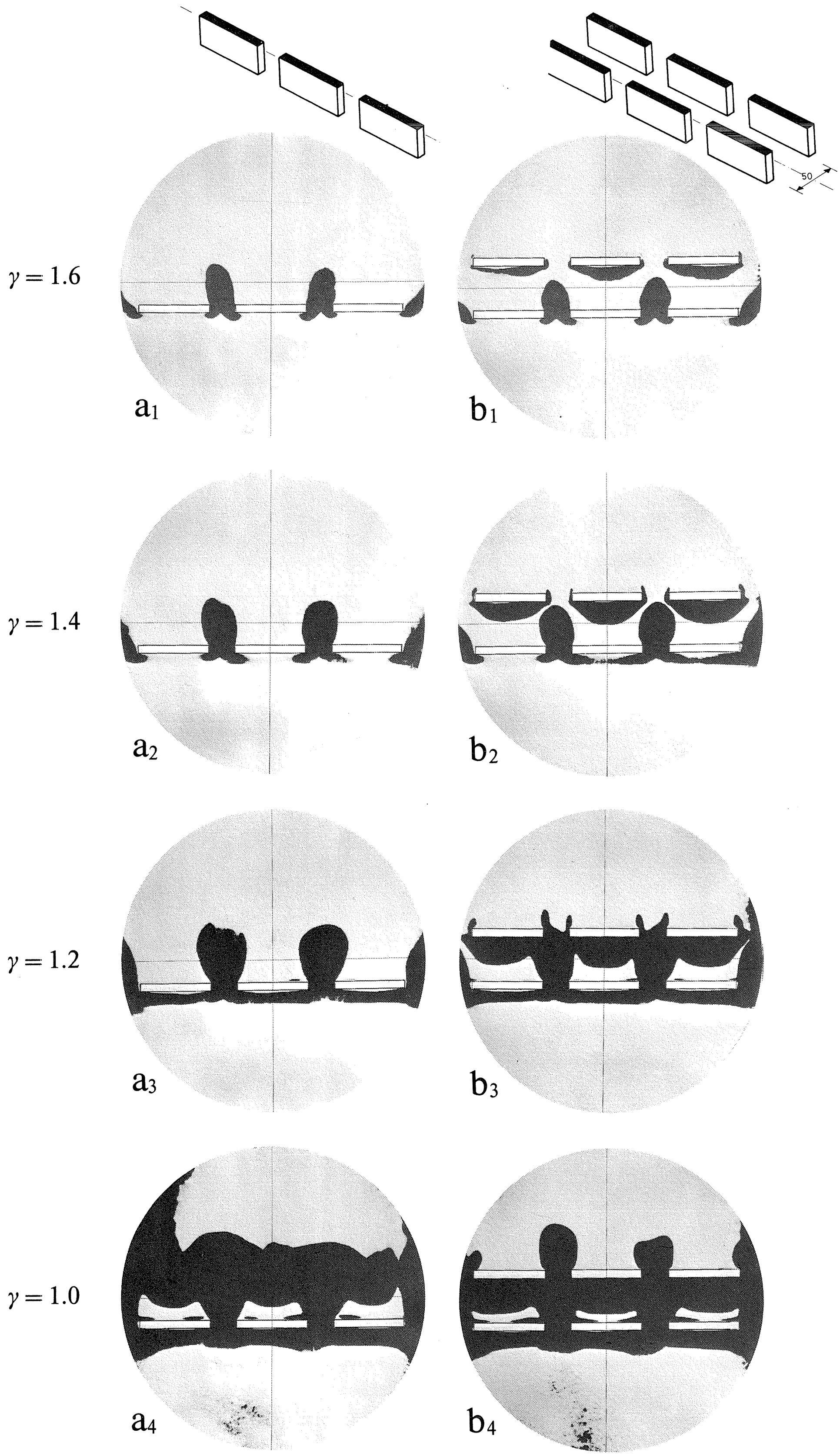


Fig. 16. Wind perpendicular to one row of slab blocks (a) and two rows of slab blocks (b) ($b \times l \times h = 10$ m $\times$ 80 m $\times$ 35 m; $t = 30$ m) $\gamma = 1.2–1.4–1.2–1.0$.

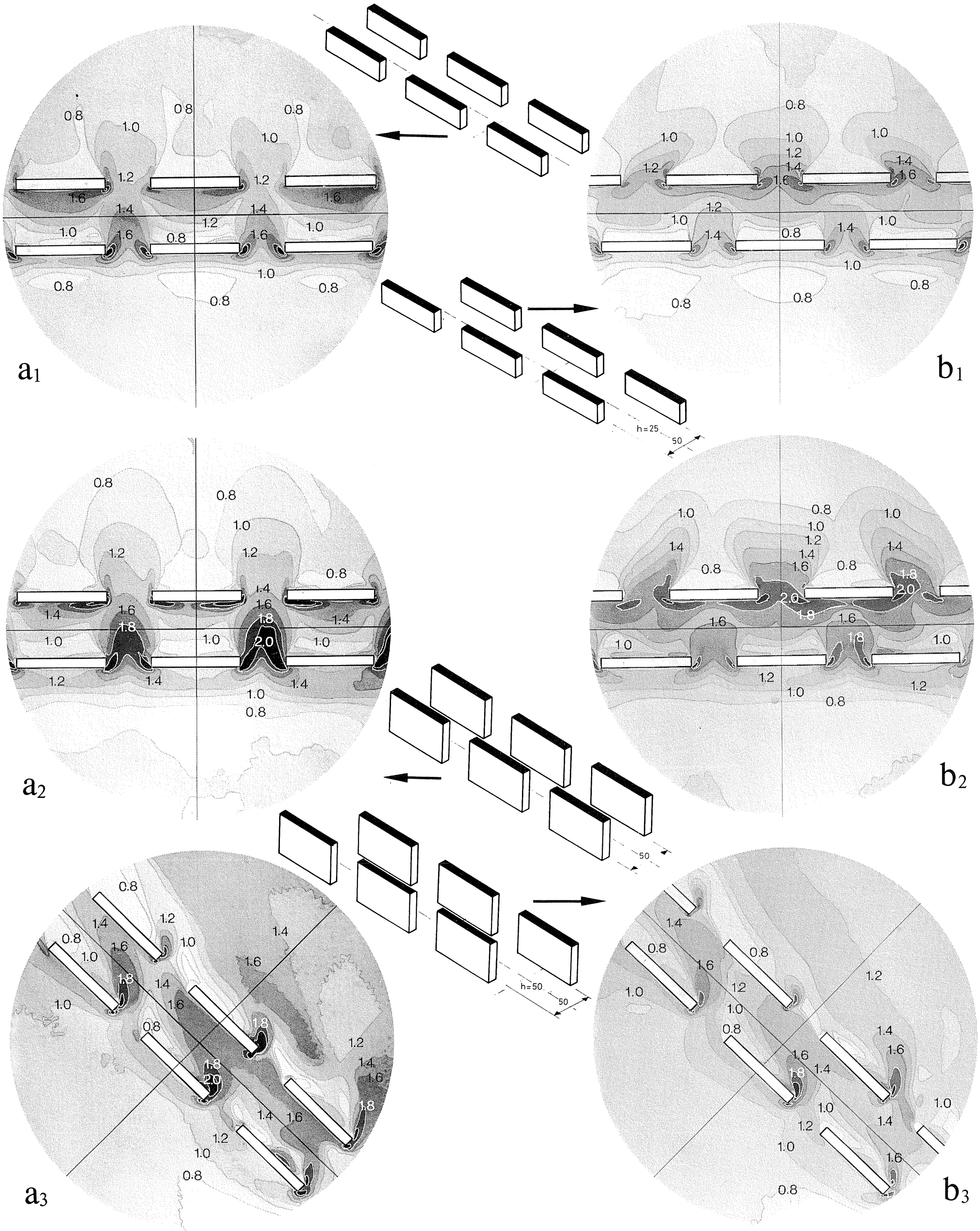


Fig. 17. Two parallel row of slab blocks; street width $s = 50$ m, distance between the blocks $t = 30$ m

a. blocks not shifted towards each other

b. blocks shifted towards each other

a_1–b_1. $b \times l \times h = 10$ m $\times$ 80 m $\times$ 25 m; $\varphi = 0°$

a_2–b_2. $b \times l \times h = 10$ m $\times$ 80 m $\times$ 50 m; $\varphi = 0°$

a_3–b_3. $b \times l \times h = 10$ m $\times$ 80 m $\times$ 50 m; $\varphi = 45°$

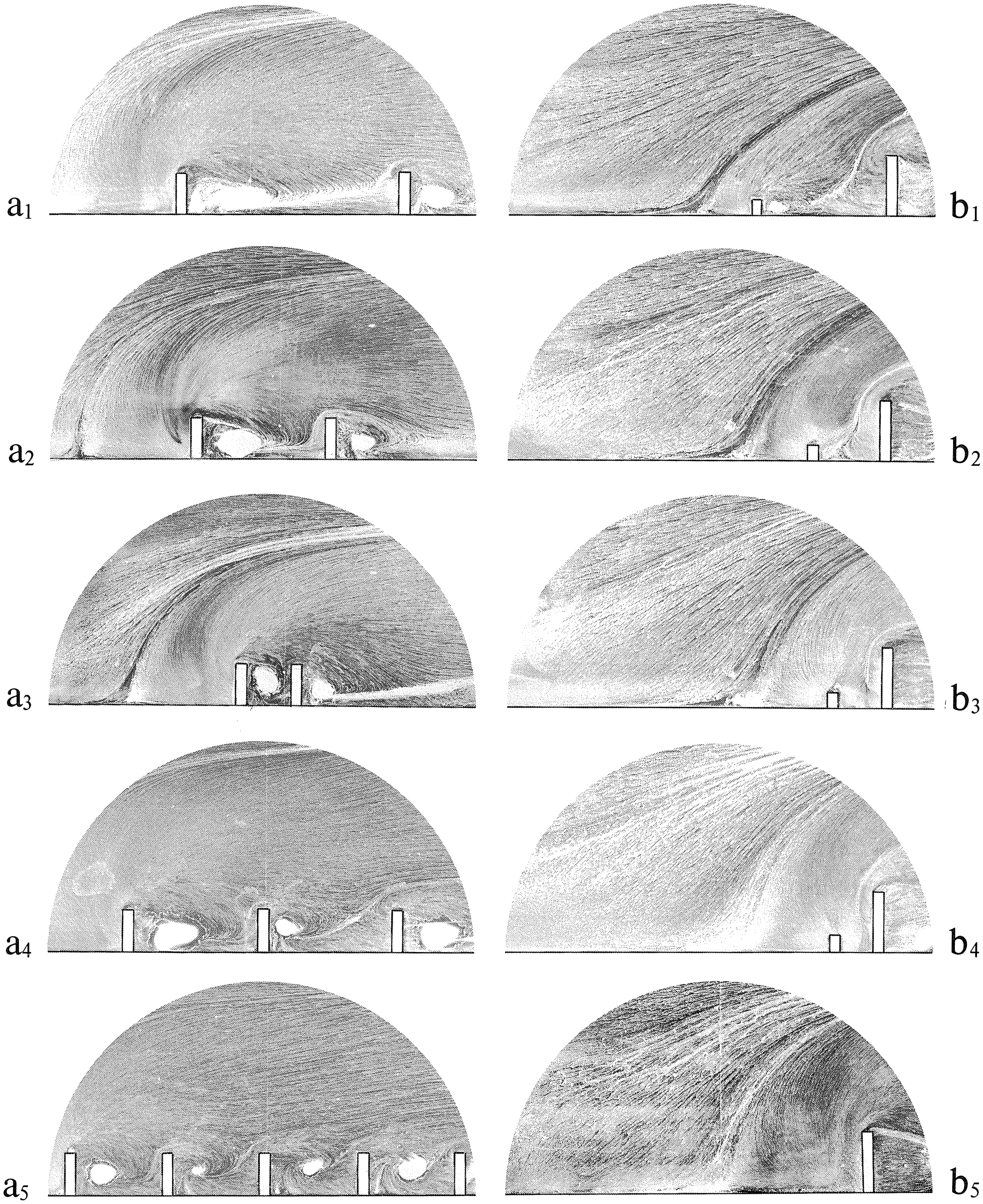


Fig. 18. Two-dimensional air flow patterns
a. equal building height $h = 35$ m
distances $s = 170-100-35-100-70$ m
b. low building ($h = 12.5$ m) in front of a high building ($h = 50$ m)
distances $s = 100-50-35-25-0$ m.

There is a second category of building configurations, however, where the total discomfort is considerably greater than could be expected from the basic cases. Configurations of only parallel buildings more particularly belong to this category, with the only exeption of one row of parallel buildings all in line, as in Fig. 16a. As soon as a second row of parallel buildings is present, the situation changes, however. A good example is a street with parallel buildings on both sides, as in Fig. 16b. If the wind is blowing perpendicular to the length of the buildings, then the normal discomfort pattern will occur, in the first row with reverse air streams in front of each building and high corner streams between the buildings. Between the two rows a standing vortex will try to develop just as in the case of a two-dimensional, air flow, see Fig. 18a. Due to the gusty character of the wind, the velocity perpendicular to the street and also the air-pressure will vary along the street. So the air stream in the street will be transported in an irregular way to the left and to the right (see Fig. 9 of the previous article). These transverse air streams will decrease with increasing distance between the blocks and will not develop if the blocks along the street are of no substantial size, compare Fig. $19a_1$.

In the openings between the buildings of the first row in Fig. 16b high corner streams are to be expected, but this is not an unbroken airstream, as the corner streams between the buildings of the second row are much smaller. A carefull study of Fig. 16 is very enlightening. In Fig. $17a_1$ and a_2 complete discomfort maps for this situation are given for buildings 25 m and 50 m in height.

The situation changes completely, however, if the buildings of the second row are shifted half a block towards the buildings of the first row, see Fig. $17b_1$ and b_2.

Now there are also strong corner streams between the buildings of the second row whereas the corner streams in the first row have decreased. This could be due to the buildings of the second row, which block the air stream through the openings of the first row. So some more wind will be transported over the first row of buildings, but transported downwards behind these buildings in front of the second row.

For wind incident at 45° the discomfort maps are given in Fig. $17a_3$ and b_3. Especially in the situation where the blocks are shifted towards each other (Fig. $17b_3$) the discomfort is reduced; evidently, the wind can now more easily go through the configuration.

Another very sensitive configuration consists of parallel blocks, but not located in one line, see Fig. 19. In Fig. 19a the first building on the windward side is affected in the usual way, whereas the second and the third building are in the wind shadow of the first building. The buildings are not long enough to develop transverse air streams to some extent. But as soon as the wind direction forms a small angle with the long axes of the building, transverse air streams will begin to develop and the discomfort between the buildings increases. The maximum discomfort will occur for an angle of 45°, see Fig. 19c. Only for wind parallel to the long axis of the building will there be no interaction at all; this means no extra discomfort, but no extra shelter either, see Fig. $20b_1$. In Fig. 20 some examples are shown where the buildings are shifted towards each other over half the length of the blocks. The discomfort will reach a relative minimum if the effective area of the buildings directly exposed to the wind is a minimum, see Fig. $20a_2$. Strong

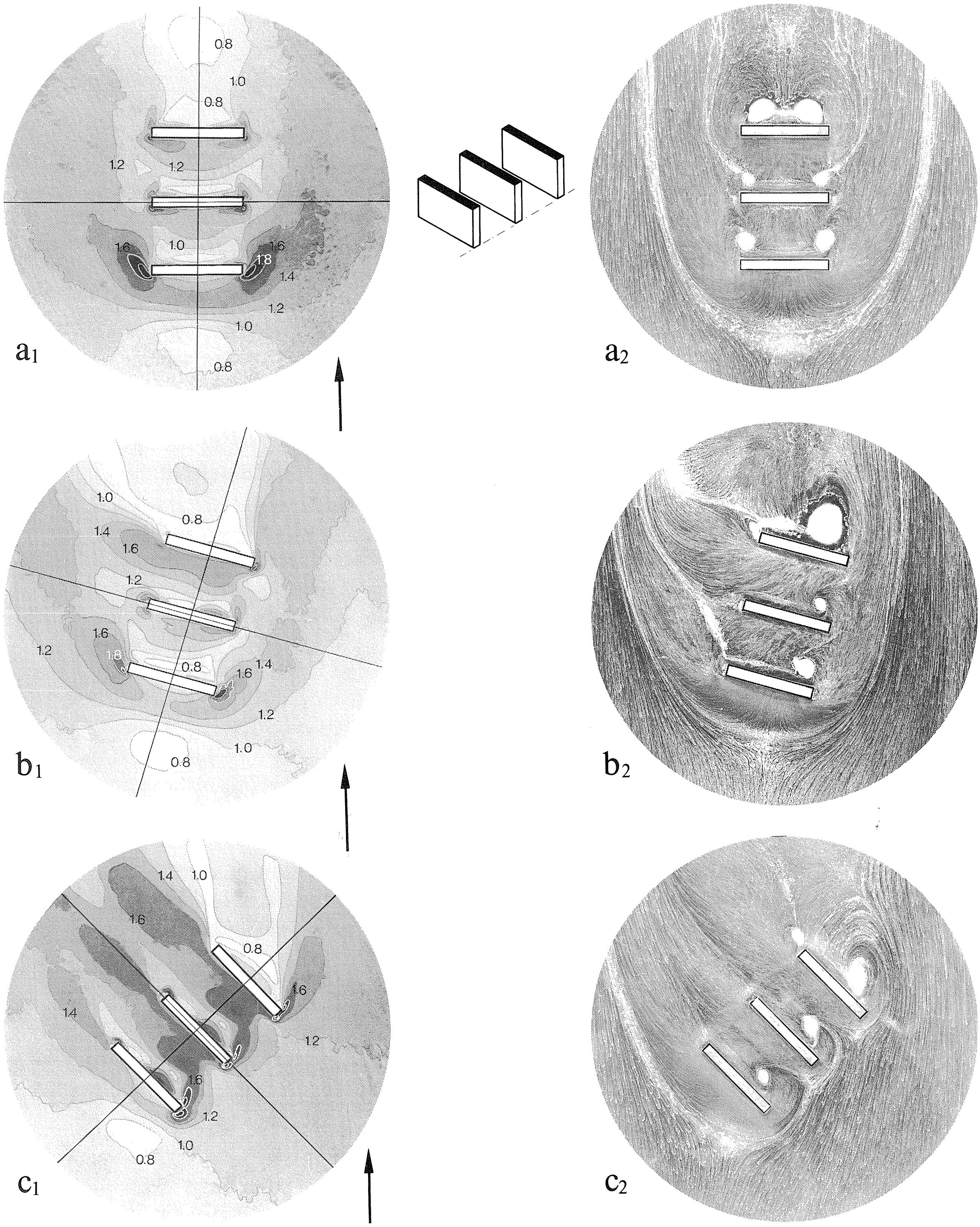


Fig. 19. Three parallel high slab blocks ($b \times l \times h = 10$ m $\times$ 80 m $\times$ 50 m).
Distances between the blocks $s = 50$ m
a. $\varphi = 0°$
b. $\varphi = 15°$
c. $\varphi = 45°$

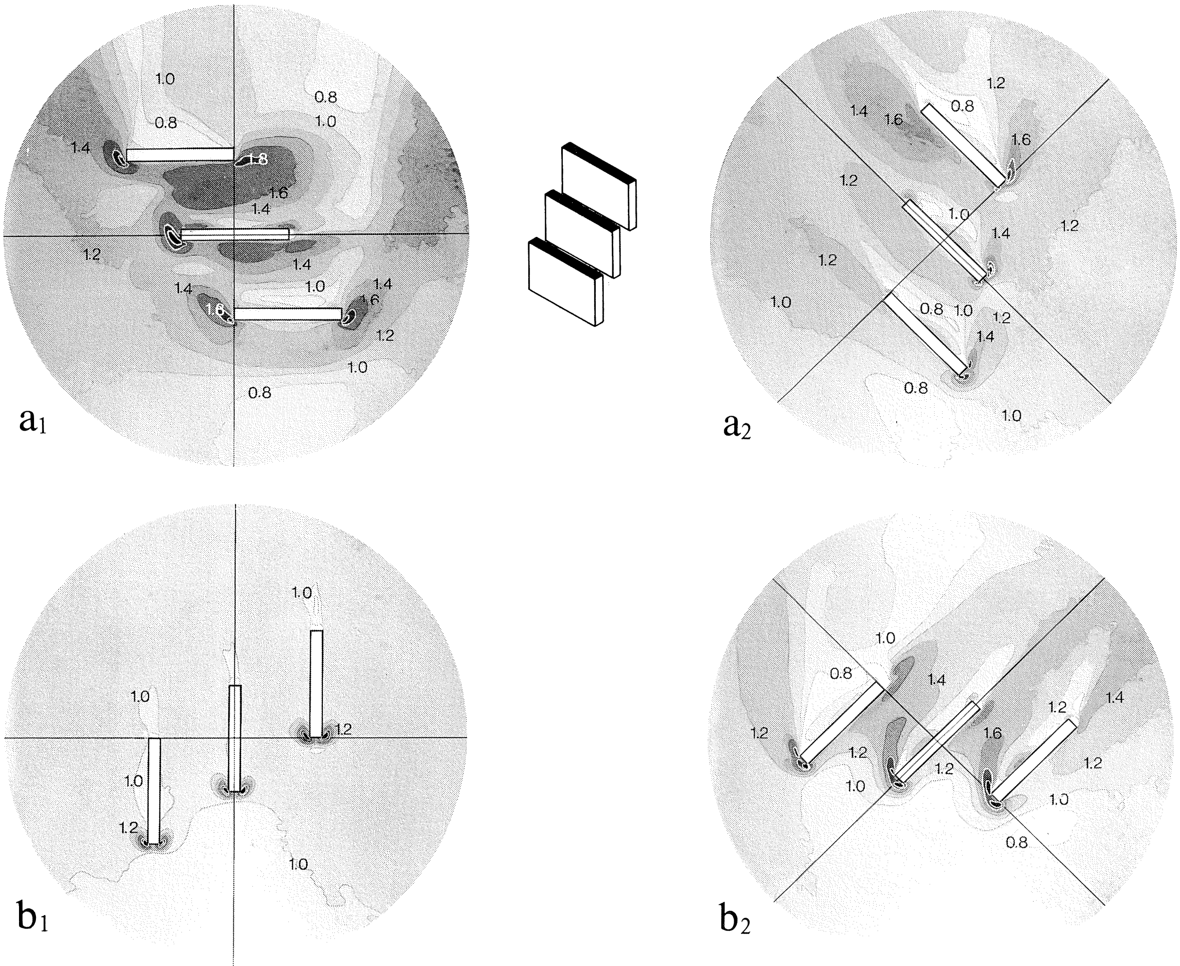


Fig. 20. Three parallel slab blocks shifted half a block length towards each other ($b \times l \times h = 10$ m $\times$ 80 m $\times$ 50 m; $s = 50$ m) $\varphi = 0°\text{–}45°\text{–}90°\text{–}135°$.

transverse air streams now also occur for wind perpendicular to the long axes of the buildings, see Fig. 20a1.

An absolute minimum will occur if the wind is parallel to the long axes of the buildings, see Fig. 20b1.

In Fig. 21 the buildings are displaced over the full block length. The main reason for the great discomfort associated with most wind directions is that four effects will intensify each other, see Fig. 22:

a. The downward air streams behind the first building.
b. The downward air streams in front of the next adjacent building.
c. The corner streams which are now guided between the buildings.
d. The pressure difference on each side of the corridors.

In the Netherlands such configurations have not infrequently been adopted for build-

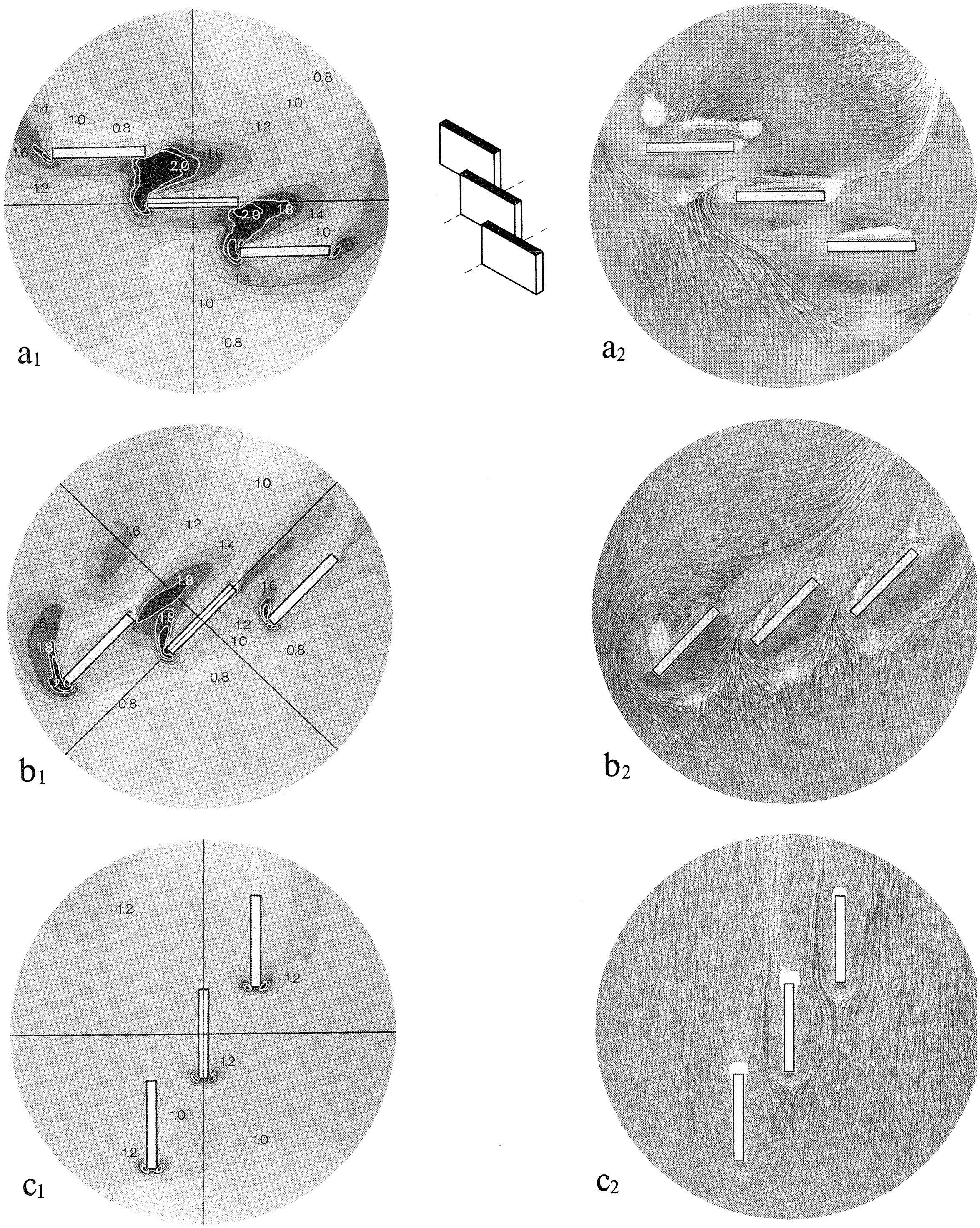


Fig. 21. Three parallel flats shifted a full block length towards each other
($b \times l \times h = 10$ m $\times$ 80 m $\times$ 50 m; $s = 40$ m)
a. $\varphi = 0°$
b. $\varphi = 135°$
c. $\varphi = 90°$

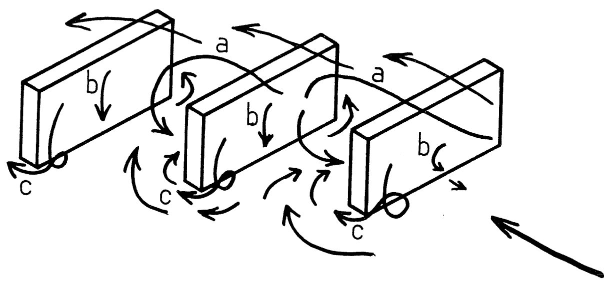


Fig. 22. Stylized air flow pattern for parallel buildings, shifted towards each other (a, b, c see text).

ings at the boundaries of a town, often directly facing flat open fields. Numerous complaints about wind environment are heard. The only way to reduce the discomfort in such situations seems to be the planting of trees and shrubs or the erection of semi-permeable screens to throttle the wind streams. These methods are especially effective at the corners of buildings, but also in the open space in between the buildings.

8 Influence on the environment by design features of buildings

Apparently an obvious solution is to surround a high building with a much lower part, one to three storeys high. The corner streams are then kept away from the pedestrians at walking level. But the combination of upward air streams caused by the lower part and downward air streams and corner streams from the higher part will cause much trouble on the sides of the lower building, so the improvement is not really very effective. The trouble has just been displaced. In Fig. 23 the discomfort and streamline maps are shown for a high building with and without a lower surrounding part.

The situation where a low and rather long building is in front of a high building is well known in a negative sense, as a standing vortex behind the low building will try to develop, just as in a two-dimensional situation, see Fig. 18b. Photographs of a three-dimensional situation with and without the lower building are presented in Fig. 24.

Inspection shows that the size of the affected area in front of the high building is somewhat increased, but that the discomfort is not greatly increased. On the other hand, the corner streams from the high building will be decreased by the upward air stream from the low building. So it seems that the trouble to be expected is somewhat over-estimated.

If two buildings are close together, a small passage between them is greatly affected by their corner streams. Now a lower part between the two buildings will also cause an upward air stream between them and will decrease the corner streams of the high buildings. The environment will improve considerably. The situation with and without the lower part is shown in Fig. 25.

A similar positive effect will also be produced by lower parts at the narrow sides of a high building; in front of the high building a calmer zone can be expected.

Another effective way to improve the environment is to design two or three storeys of

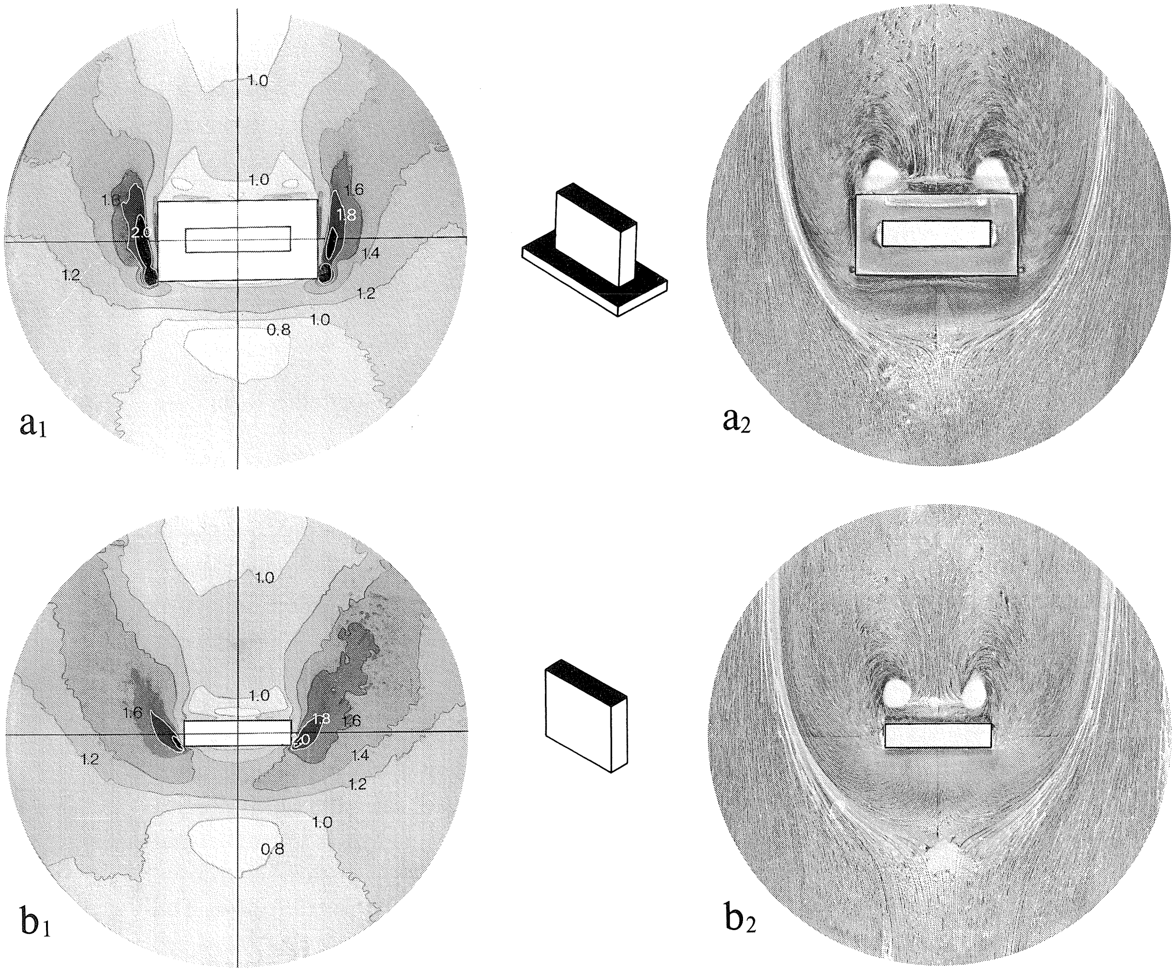


Fig. 23. High building with and without a surrounding lower part
high building $b \times l \times h = 20\ \text{m} \times\ 80\ \text{m} \times 70\ \text{m}$
lower part $b \times l \times h = 60\ \text{m} \times 120\ \text{m} \times 10\ \text{m}$.

the building - not too far above the ground - with a wider ground-plan, see Fig. 26a. In the direct vicinity of the corners the environment will then improve because the downward air streams are deflected in this way. Similar results are obtained with canopies. Just making the building smaller at walking level - around the whole or part of the circumference of the building - offers hardly any advantage, see Fig. 26b.

9 Main results and approximate rules

9.1 *Validity*

a. Wind profile
In all the tests it is assumed that the buildings are situated in surroundings where the coefficient of the vertical wind profile is $\alpha = 0.28$.

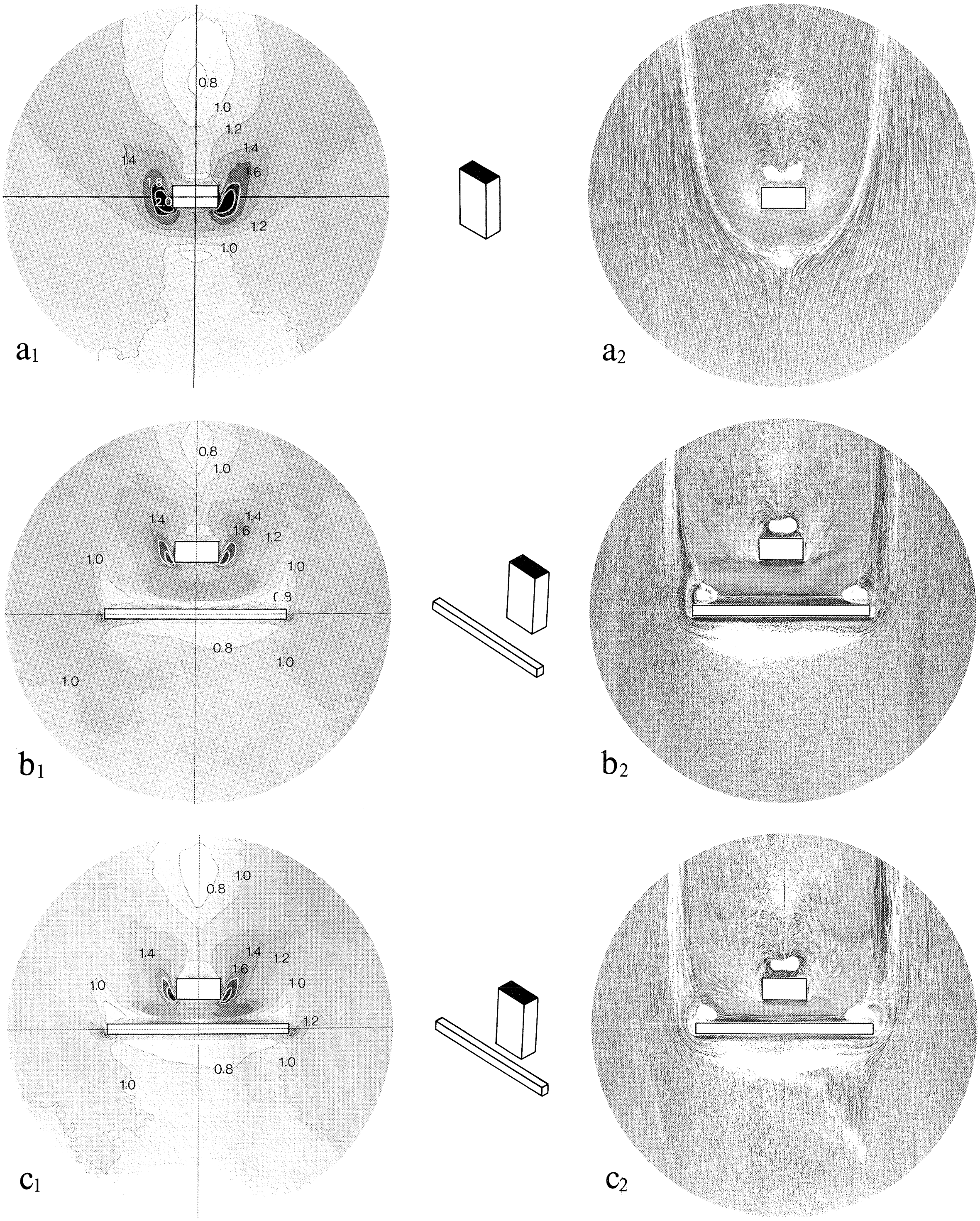


Fig. 24. Long low building in front of a high building

a. high building alone ($b \times l \times h = 20$ m $\times$ 40 m $\times$ 70 m)

b. long low building ($b \times l \times h = 10$ m $\times$ 10 m $\times$ 160 m) in front of the high building (distance between the buildings $s = 40$ m)

c. as b, but distance now $s = 20$ m.

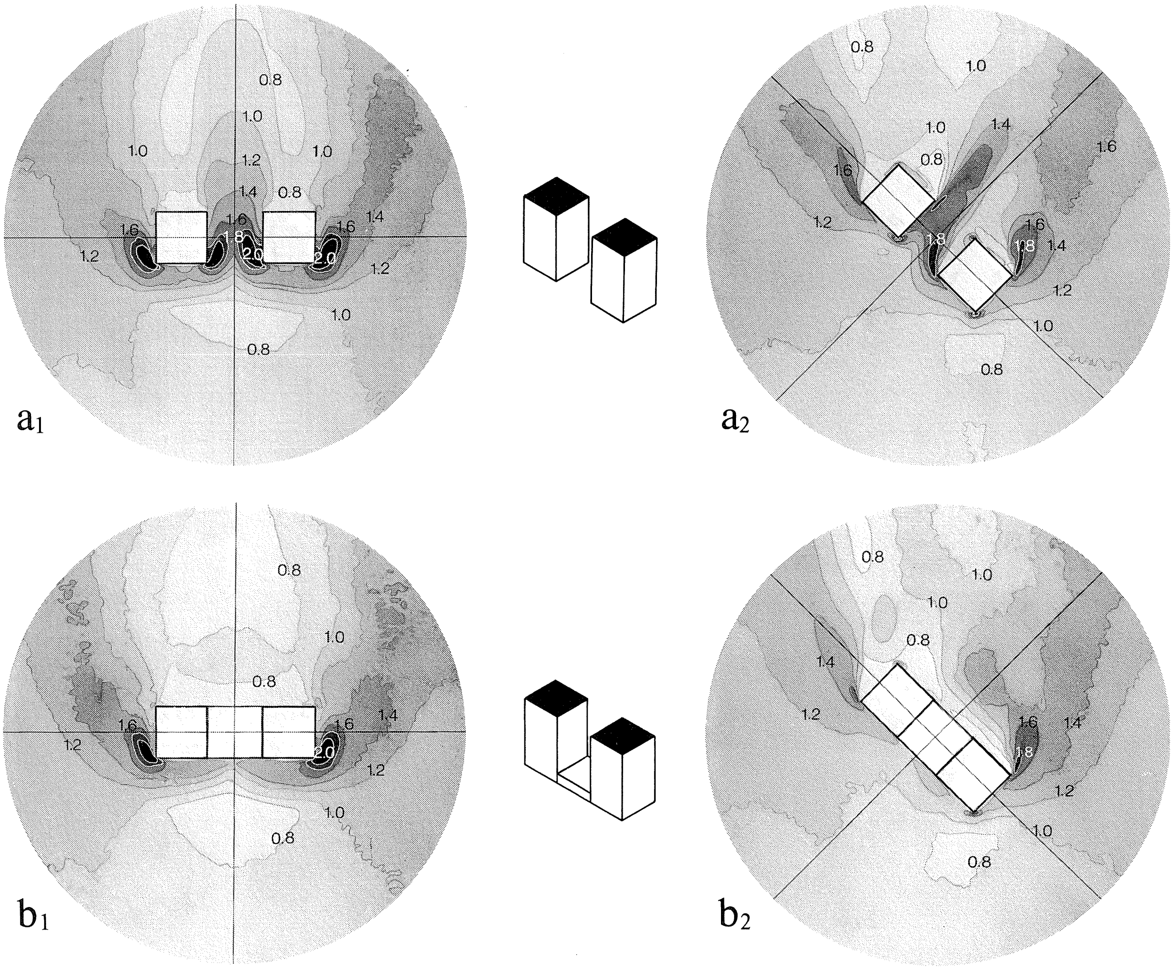


Fig. 25. Low part of the building between two high buildings
a. high building alone ($b \times l \times h = 40$ m $\times$ 40 m $\times$ 70 m)
b. low part of the building between the high buildings (lower part: $b \times l \times h = 40$ m $\times$ 40 m $\times$ 10 m).

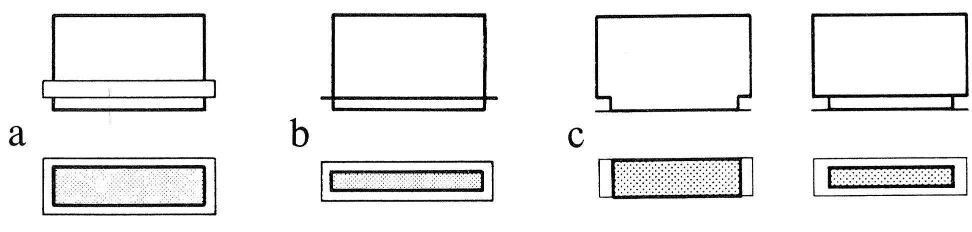


Fig. 26. Measures to improve the environment in the direct vicinity of the building
a. a few storeys with a wider ground-plan
b. canopies
c. smaller ground-plan at walking level is ineffective.

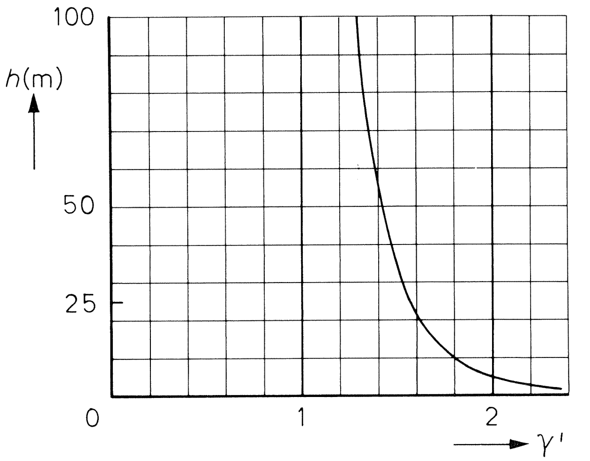


Fig. 27. Magnification factor to convert the wind speeds as obtained by the tests in a built-up area to wind speeds in flat open terrain (high buildings on the edge of the built-up area). It is assumed that the wind speed at the top of the high building governs the environment.

b. High buildings at the edge of the built-up area
If the high building is situated at the edge of the built-up area and if the prevailing winds blow over flat open country or open water, the wind speeds may be higher than assumed in the tests. In Fig. 27 a rough indication is given of the increase in wind speed in such circumstances, dependent on the height of the considered building.

c. Regular configurations of low or medium-high buildings
If the edge of the built-up area consists of a regular configuration of low or medium-high buildings it can be assumed that the wind profile according to point a. is established after passing a narrow edge zone consisting of one or two basic configurations. The test results are also applicable to high buildings located in this narrow edge zone.

d. Open space
If in a built-up area open spaces are available with an area of 400 m × 400 m or more, it is assumed that the wind speed profile for flat open country is re-established. For the built-up area which is encountered by the wind after passing the open space, the magnification factors of Fig. 27 can again be adopted.

9.2 *Single high buildings*

a. Influence of the dimensions of the building on the environment
The wind discomfort due to a building is primarily dependent on the dimensions of the building itself. The following rules are applicable:
- the height of the building has a dominant influence on the environment;
- the length of the windward face of the building has a strong influence;
- the width of the building (face parallel to the wind) has a minor influence.

b. Wind discomfort area

As a measure for the environment the so called wind discomfort area A^* has been adopted, i.e., the area (in m^2) where the wind discomfort parameter γ reaches a value equal to or larger than $\gamma = 1.6$.

For wind perpendicular to a face of the building the magnitude of A^* can be determined from Fig. 18 of the previous article. For varying wind direction an approximate formula can be used (formula (1) of the previous article).

c. Magnitude of the discomfort

The following approximate rules can be adopted:

- wind discomfort is slight if:
  1. the building is less than 25 m high;
  2. the width of the windward face is less than 15 m (independent of the height of the building);
- wind discomfort to be determined with the help of Fig. 18 of the previous article if:
  1. the height ranges from 25 m to 50 m for each length;
  2. the height ranges from 50 m to 100 m and the length is not more than 80 m.
- wind tunnel investigation is highly recommended if the height exceeds 70 m and the length moreover exceeds 50 m.

d. Wind regime

Depending on the length-height ratio of the windward face of the building, three types of airflow are distinguished, which should be fully understood (Fig. 13 of the previous article). The types of air flow belong to the following types of windward face of the building:

- tall face ($h > 3a$)
- face of the transitional type ($h \approx a$)
- long face ($a > 3h$)

e. Influence area

Around each single building there exists an area where the wind speed and wind direction are strongly influenced by the building itself (Fig. 20 of the previous article). Wind speeds are greatly increased and decreased, and turbulence is locally much greater than outside this area:

- for a tall windward face this area is only dependent on the length of the windward face ($R = 1.8a$, for $h > 1.25a$);
- for a windward face of the transitional type the area is dependent on the height as well as on the length of the windward face ($R = 1.6\sqrt{ah}$, for $0.33a < h < 1.25a$);
- for a long windward face the area is dependent only on the height of the windward face ($R = 2.8h$, for $a > 3h$).

The size of the area can be reasonably well described by a circle with radius R and in the last case by two circles with radii R.

9.3 *Building configurations with weak interaction*

For certain building configurations the wind discomfort can be determined by superimposing the wind discomfort patterns which are valid for the single buildings of which the configuration is composed. In such cases each building with the matching wind discomfort map is drawn and the largest area for each value of the wind discomfort parameter is taken into account. If there are axes of symmetry, each wind discomfort pattern is valid just up to the axes of symmetry. So there is no superposition of the wind speeds.

This rule is valid for the following building configurations:

a. Two or more parallel buildings with the long axes on one and the same line, Fig. 28a. For long buildings there is no interaction if the distance between the buildings is greater than 2.5h.

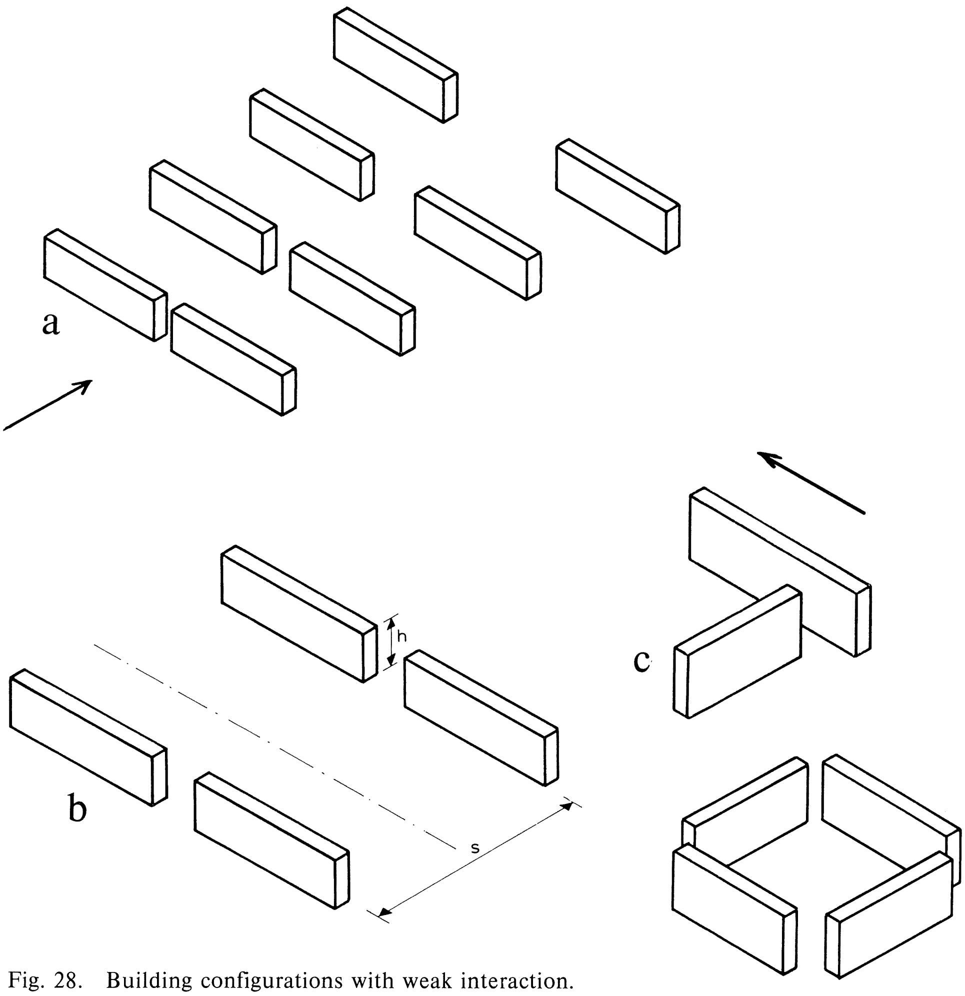


Fig. 28. Building configurations with weak interaction.

Superposition is possible for distances between the buildings varying between $2h$ and $0.5h$.
For distances between the buildings less than $0.25h$ the two buildings will act more or less as one building.
The wind speeds in the opening remain more or less unchanged and the affected area is proportional to the width of the opening.
Overrolling vortexes are possible for wind directions between 30° and 60° if the length of each separate building is larger than 3 times the height.

b. Two rows of parallel buildings which are spaced farther apart than 5 times the height. For decreasing distance between the two rows very objectionable interaction may occur.
c. Configurations of building blocks where the long axes are alternatively perpendicular to each other, see Fig. 28c. This rule is valid for all wind directions. So for long buildings most discomfort will be experienced at the windward edge of the building. This means that "wind spreading" configurations cause more discomfort than "wind catching" configurations.

9.4 *Building configurations with strong interaction*

For another type of building configurations the discomfort can no longer be determined by a kind of superposition and the discomfort is considerably greater than might be expected from the wind discomfort maps for the single buildings. This is mainly due to the fact that air streams, which can flow away unobstructedly around a single building, are now guided between the buildings and thus cause much higher velocities and therefore greater discomfort.

This strong interaction occurs principally for all configurations of long blocks or blocks of the transitional type if the configuration is of some appreciable extent or if the distances between the buildings are less than 5 times the height.

Some of the most frequently encountered configurations are (see Fig. 29):

a. Configurations of three or more slab blocks whose long axes are parallel and where the blocks may or may not be shifted towards each other.
   For almost all wind directions strong interaction will occur between and behind the flats because of transverse air streams. The discomfort is determined by the effective affected area, i.e., an absolute minimum of discomfort if the wind is parallel to the long axes of the buildings and a relative minimum if the buildings are in each other's wind shadow.
b. A row of parallel blocks on either side of a street. The normal wind discomfort pattern is found on the windward side of the first row for wind blowing perpendicular to the row. Strong transverse air streams will occur on the windward side of the second row. Considerable discomfort in the opening between the buildings in the first row and much less in the second row. But as soon as the buildings in both rows are shifted towards each other (or the wind is no longer perpendicular to the buildings), the discomfort in the openings of the second row is greatly increased.

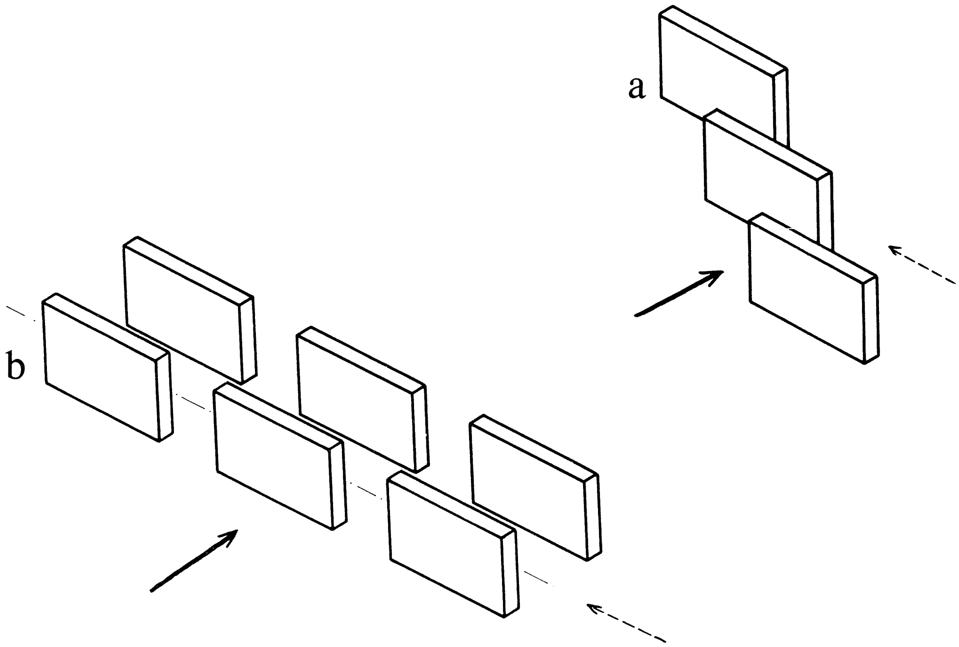


Fig. 29. Building configurations with strong interaction.

9.5 *Influence of low buildings around high buildings*

If building configurations consist only of low or medium-high buildings, the wind speed will be locally increased. Values of the wind discomfort parameter such as $\gamma = 1.2$–1.4 have to be accepted as normal at the corners of the buildings. The maximum discomfort in the direct vicinity of high buildings is determined by the dimensions of such buildings. The surrounding buildings of medium hight do have some sheltering effect at some distance from the high building. The sheltering effect in the near vicinity of the high building is greater according as the height of the high building is more nearly equal to that of the surrounding lower buildings. A long block of medium height in front of a high building may cause some extension of the affected area. The effect remains small, however, and at the corners of the high building some improvement may be expected.

Attention must be paid to lower buildings on the leeward side of high buildings, because in this zone the various vortexes may cause some trouble with smoke flow.

9.6 *General considerations for the creation of good environment*

a. Situation of the building

The orientation of the building in relation to the prevailing wind directions (prevailing in time and magnitude of the wind speed) plays an important role in reducing wind discomfort. Complaints are generally to be expected when really strong winds occur.

b. Dimensions of the faces

One should try to choose the dimensions of the faces in such a way that the wind environment area is as small as possible. If the building is lower than 25 m, generally no substantial increase in wind discomfort is to be expected.

c. Increased shelter

If increased shelter around a building is desired (children's playground, home for the aged) all the year round the following points are essential:

- make sure that the building itself does not cause wind discomfort (choose building dimensions within the region in Fig. 18 of the previous article which is designated as: "environment satisfactory");
- take care that the building is outside the influence area of high buildings in the vicinity;
- do not locate the building in a completely open area, but in an area with low buildings or some vegetation; do not locate it at the edge of a built-up area, facing flat open ground, unless no significant wind is expected to blow from that direction.

If the desired shelter is limited to seasonal use (terraces), the occurring wind speeds and directions for each individual month should be examined. Wind screens around terraces are effective only against more or less horizontal air streams. Check if downward air streams are to be expected.

d. Vegetation

If sufficient shelter cannot be obtained by the methods indicated in c., only the application of trees or shrubs at some distance from the building will improve the environment. High wind speeds at building corners should be reduced by means of vegetation or semi-permeable wind screens at these corners.

e. Low parts of the building connected with high parts of the building

A surrounding lower part around a high building is not very effective. The downwards air streams are not reduced in magnitude; together with the upward air streams introduced by the surrounding lower parts of the building, new areas with vortexes and increased wind discomfort are to be expected at the corners and the sides of the lower building parts. These air streams are hardly less severe than the original air streams. Only on the windward side of the lower building part is the environment improved.

Also, a local lower part of a high building at the corners or the short sides of that building may have some effect in front of the building as the wind speeds are reduced here. The effect is more or less comparable with that of a building with wings.

A connecting lower part between two high buildings can be very effective, as the discomfort in front of and behind the low part of the building is much less than in the case where there is an opening between the two high buildings. The upward air streams caused by the lower building improve the environment as the downward air streams of the high buildings now reach the ground farther away from the building.

f. Canopies around a building or a storey with a larger area (some distance above the ground)

To protect the direct vicinity of the high building, especially such arrangements are effective which direct the downward air streams away from the building and partly to both sides of the building.

The improvement is greater the more the extra width of the canopy or broadened storey is increased. But at some distance from the building wind speeds will now occur which would have occurred at the corners without those special arrangements.

g. Openings under buildings

Openings under buildings will practically always cause increased discomfort and should be avoided as much as possible. If only pedestrians are using such passages, the environment can be considerably improved by applying wind screens in the opening. The air streams will be stronger according as the difference in air pressure on the windward and leeward face of the building are greater, so the phenomena are most objectionable for high and long front faces.

Buildings with some open space under them and supported by columns or shear walls will always have a disagreeable environment under the building, and this space is not suited for social activities.

Shear walls cause much more strongly directed airstreams than columns. Around the cores of such a building there is greater discomfort, almost as much as at the corners of a traditional building.

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