Effects Due to Groups of Buildings [and Discussion]

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Effects due to groups of buildings

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For the past 5–10 years architects have realized the need for information on the aerodynamics of the environment around groups of buildings. The high wind speeds in precincts around tall or exposed buildings have surprised their designers who have sought remedies, and the publicity about windy environments around existing buildings has led to requests for advice about developments on the drawing board. In the absence of a general theory for the prediction of air flow patterns and wind speeds around groups of buildings, the problem has been studied in wind tunnels.

The paper describes typical town centre developments in which a problem of wind environment has arisen, and gives a brief account of the investigation of specific cases. The broad conclusions from some twenty case studies made by the Building Research Station in response to inquiries from industry are summarized. In seeking to generalize, a series of investigations of the air flow around small groups of idealized model buildings has been conducted, and some comparisons between model and full-scale measurements have been made. This has led to a design method for use in planning the layout of small groups of buildings, which draws on the data from model tests and also meteorological information and comfort criteria. This work is outlined, and future research needs are also discussed.

The first modern high buildings for occupation were erected in America towards the end of the nineteenth century in the search for prestige and more intensive site exploitation. They were made possible by the development of steel structures and elevators. Similar buildings were then considered impracticable on London clay owing to foundation problems. Development in the U.K. in this period and until the 1940s was in the form of corridor streets—the familiar arrangement of buildings of a few storeys height erected along the street line. This type of layout stemmed from the first Building Act after the Fire of London which limited the heights of buildings by prescribing angles of elevation, taken from the opposite side of the street, within which development should take place. This method of control provided a measure of daylight as well as reducing the risk of firespread, and it was gradually adopted for most urban areas. It became clear by the 1940s, however, that there was a conflict between economic considerations leading to a demand for high density of buildings and the requirements of a reasonable standard of daylighting.

Studies before and during the war on the relation between density and daylight showed that the corridor type street was one of the least efficient from the daylighting point of view (Crompton 1955). It was found that by turning every other building through 90°, so that adjacent buildings were at right angles, there was a marked improvement in daylighting for the same density. This work suggested the open plan layout in which buildings would be taller, drawn back from the street and concentrated in the central parts of sites. Such considerations, together with modern development in structures and pile foundations, led to the situation today where small groups of towers or slabs dominate the urban scene. Tall buildings present a range of problems to their designers, not the least of which are in the aerodynamic field. Wind loading is a major consideration but problems related to the air flow round tall buildings also arise. For example, the convection coefficients affect the heat transfer between a building and its surroundings; air flow may affect rain penetration and weathering; wind may create noise which is accentuated in the taller buildings. In this field, however, apart from inquiries concerning wind loading, the wind environment in pedestrian precincts around groups of tall buildings has brought in the greatest number of inquiries to the Building Research Station in recent years. Since the earliest concerning new centres at Croydon and Leeds were dealt with in 1964, when no guidance to designers on this matter was available, some 200 inquiries about either existing or projected developments have been received, of which perhaps one-tenth have been studied in some detail, either by wind-tunnel investigation or more recently by visual examination of a model and drawing on experience to make recommendations. Some similar cases have been handled by the National Physical Laboratory and universities, perhaps the earliest being a test at Liverpool University of a model on the proposed town centre at Cumbernauld. The emphasis in the present paper has, therefore, been given to wind environment near the ground. General points concerning flow around buildings are first made. Some work done at the Building Research Station in seeking to generalize and provide design information for architects is described. Case studies of groups of buildings in an urban setting and remedies for windy areas are outlined. The paper concludes with a discussion of design information and future research needs.

INVESTIGATION USING IDEALIZED MODELS

The general flow pattern around tall buildings and the main regions where an accelerated flow is likely near the ground are of primary interest. With an isolated bluff body—such as a building—the flow normally separates at sharp front edges and a wake of separated flow is formed at the rear. The shear along the edge of the wake induces a return flow in the centre; speeds within the wake are thus generally lower than those outside and hence the wake region of a tall building is not normally troublesome from the point of view of wind environment near the ground. Conditions near the regions of separation and generally in the front of tall buildings are of greater interest from this standpoint. Baines (1965), in dealing primarily with pressure distributions, described qualitatively the flow observed at the front of a single model building in a wind tunnel. He pointed out the major difference between conditions in front of a single model in an airstream with the velocity constant at all heights above the ground—the normal method used for wind tunnel testing of buildings—and conditions when the model was mounted in a flow having a velocity variation with height, as in nature. In the latter a flow down the frontface occurred, leading into a flow along the ground away from the model. An eddy formed, in front of which the main flow separated to either side. Baines mentioned that the size of the eddy varied with time because this point of separation was not fixed by geometry.

Broadly similar observations and also velocity measurements on one or two arrangements of idealized models at the Building Research Station were described by Wise, Sexton & Lillywhite (1965). This work has been extended since then using the open jet wind tunnel described by Sexton (1965) which has a working section 1.8 m × 2.4 m in cross-section. In these studies the mean velocity of the air has varied with height according to a power law, index 0.28, following the suggestion of Davenport (1961) for conditions over a small town; a slatted screen was used to develop the gradient. Dimensions have been modelled to a scale of 1/120 and buildings up to 100 m high have been studied. Air speeds around the models have been measured by calibrated heated body anemometers, about 3 mm in diameter, that are virtually non-directional; direction was determined by a tuft of silk attached to the anemometer and by smoke studies.

The simplest case examined at the Building Research Station is illustrated in figures 1 and 2. Air flowed down the face of the slab into the space between the buildings and lateral downward

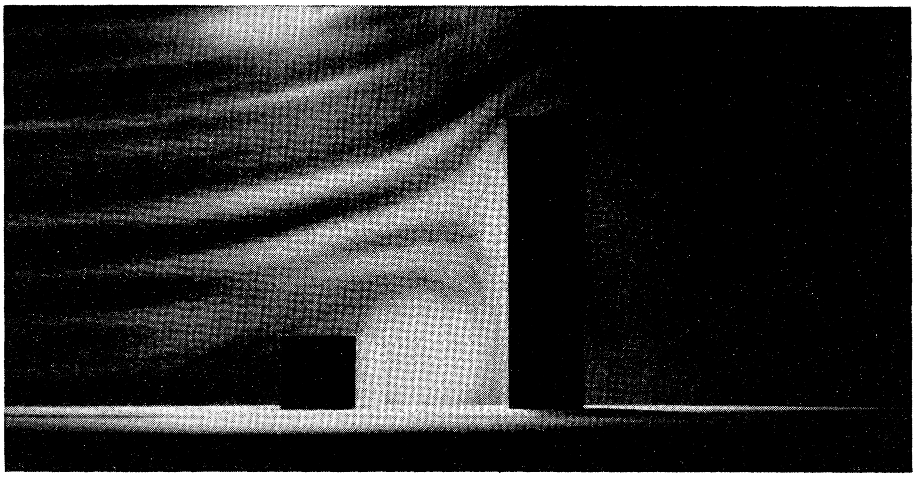

Figure 1. Flow pattern.

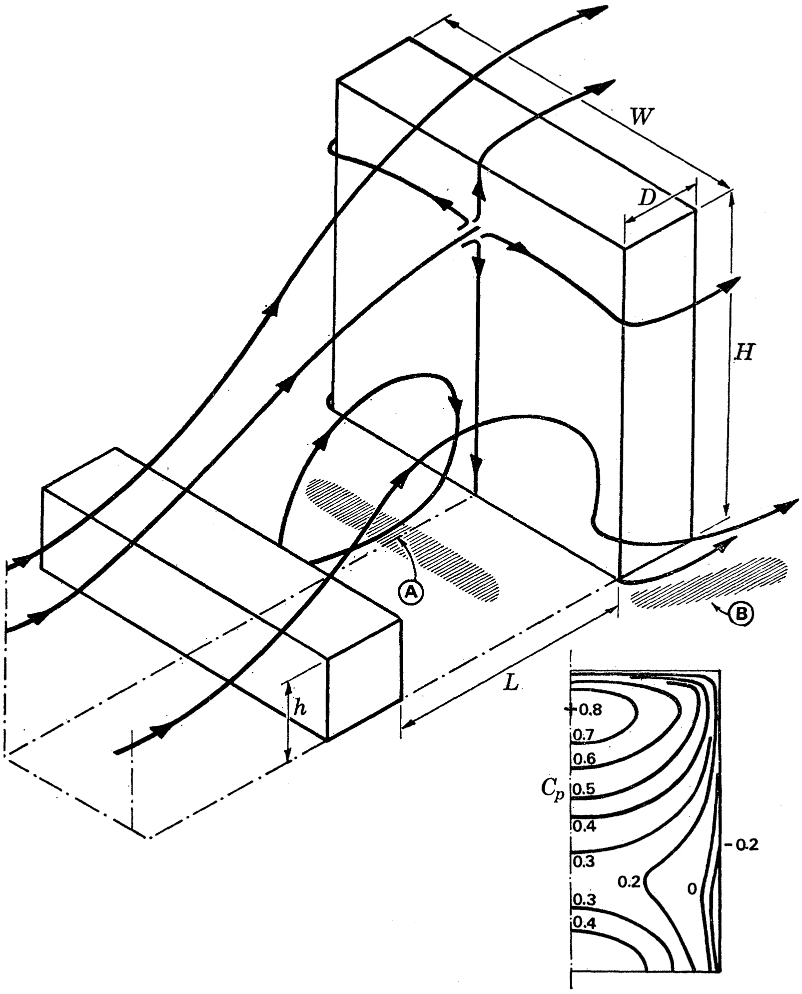

Figure 2. Typical flow pattern and pressure distribution on the windward face of a slab.

flows into the regions of separated flow occurred at the sides; the main stream of air was deflected over and round the top of the model. A typical pressure distribution on the front face of a slab is also given. Such variables as height, width and depth of the buildings, space around them, and wind orientation effect results in detail, but the major zones A and B stand out as particularly significant in respect of wind environment near the ground. Tall buildings bring down higher speed air into these areas and measurements show that mean velocities may be twice that of the free wind at the same height and three or four times that commonly experienced in towns. Investigations are in progress to find out how some of the variables with values typical of those in practice influence the mean velocities, in order to build up design information and also to help in the interpretation of some of the results obtained in the more complex situations commonly encountered. The following paragraphs describe some of the main findings so far and indicate the progress made in correlating the data. The work will be described in more detail at a later date.

SOME RECENT INVESTIGATIONS

As a first step in describing the findings in B.R.S. work it is useful to set out the basis used in analysing the data. The terms are defined in the Nomenclature and illustrated in figure 2. It was envisaged that the velocity V_A—that on the centre line of the buildings at height a in the stream near the ground—was likely to vary with the difference between the stagnation pressure on the tall building and a representative pressure at the centre of the rear face of the low building; first principles suggested a square root relationship of the form

$$V_A = \text{constant} \times \sqrt{[(C_P - c_p)\, V_H^2]}. \tag{1}$$

Interest lies in V_A relative to the velocity V_a at the same height in the approaching airstream i.e. in the ratio V_A/V_a. Equation (1) may be rewritten

$$V_A/V_a = \text{constant} \times \sqrt{[(C_P - c_p)]}\, V_H/V_a, \tag{2}$$

or

$$V_A/V_a = \text{constant} \times \sqrt{[(C_P - c_p)]}\, (H/a)^{0.28}, \tag{3}$$

because the free stream velocity varies with height by a 0.28 power law. While C_p has been measured for a wide range of conditions only a limited number of values of c_p have so far been obtained; to test the hypothesis figure 3 was prepared from the data available for a wind at right angles to the buildings ($\alpha = 90°$). The correlation is significant and it suggests that this line of enquiry is worth pursuing further. It is well known, of course, that pressure coefficients depend on geometry and, in some circumstances, on Reynolds number. To follow this up a dimensional analysis was carried out to obtain meaningful groups of the variables and gave

$$V_A/V_a = f\{V_H/V_a, \alpha, L/H, W/H, D/H, h/H, V_H H/\nu\}. \tag{4}$$

The first two groups on the right-hand side describe the approaching airstream in terms of mean velocities and wind orientation, the remainder are geometrical groups and Reynolds number. For present purposes, two of the groups may be eliminated. When D/H is small, as it is in the work described, the flow separates at the windward corners of the tall building and does not become reattached; the building then behaves similarly to a flat plate and D/H and Reynolds number may be neglected. In the present series of experiments $V_H H/\nu$ was in the range 10^4 to 10^5, only about 1 % of typical full-scale values but well above the critical range for flow around flat plates. Equation (4) thus becomes for $\alpha = 90°$:

$$V_A/V_a = f\{(H/a)^{0.28}, L/H, W/H, h/H\}. \tag{5}$$

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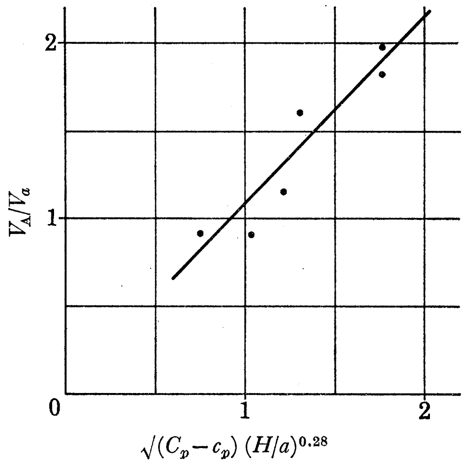

$\frac{H}{\text{m}}$	$\frac{L}{\text{m}}$	$\frac{W}{\text{m}}$	C_p	c_p
24	12	49	0.5	0.32
24	24	49	0.4	−0.07
36	12	49	0.75	0.49
36	24	49	0.8	0.38
49	49	49	0.8	(0.14)
49	49	97	0.8	(0.14)

( ), estimated

FIGURE 3. Correlation using pressure coefficients. Correlation coefficient = 0.93; $p < 0.01 > 0.001$; $a = 3$ m; $h = 12$ m.

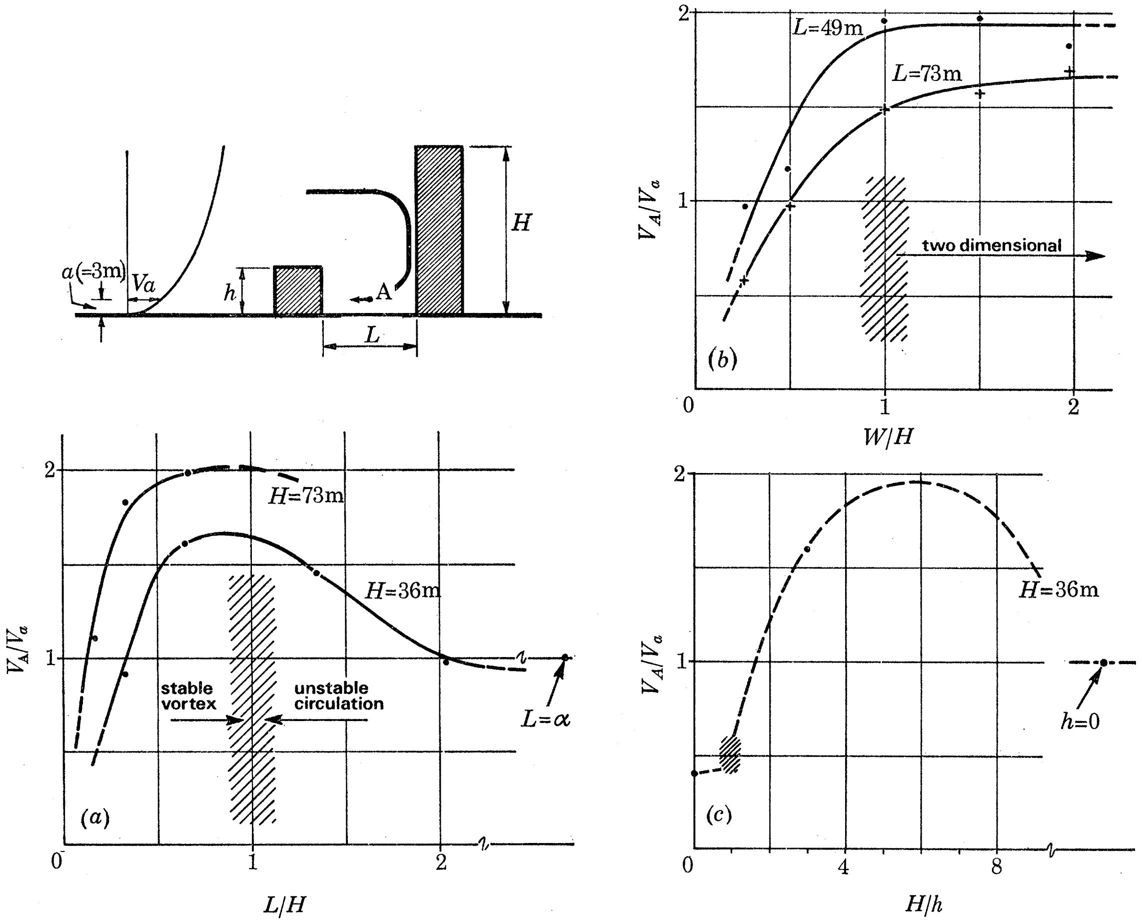

FIGURE 4. Examples of the variation of (*a*) V_A/V_a with L/H, and (*b*) V_A/V_a with W/H, (*c*) likely variations of V_A/V_a with H/h. In (*a*) $W = 49$ m, $D = 12$ m, $h = 12$ m, $\alpha = 90°$; in (*b*) $H = 49$ m, $D = 12$ m, $h = 12$ m, $\alpha = 90°$; in (*c*) $W = 49$ m, $D = 12$ m, $H = 36$ m, $\alpha = 90°$, $L = 24$ m.

Examples of the relationship between V_A/V_a and L/H with other factors constant are given in figure 4*a*; V_A/V_a increases to a maximum at $L/H \simeq 1$, and observations of the flow pattern within this range show the presence of a stable horseshoe shaped vortex near the centre of the space extending out around the large building and merging with the main stream; see also figure 1. Presumably the flow pattern changes as $L/H \rightarrow 0$ but this point has not so far been investigated. In the range $0.1 < L/H < 1$, a power law with index 0.4 gives a reasonable fit for the data so far available. As L/H exceeds 1 the flow pattern changes; there is a much less stable circulation within the space which presumably is under the influence of the wake from the low building. This circulation varies in position much as when the low building is absent. A measured value for this particular slab building on its own is given in figure 4*a*. Figure 4*b* shows the effect of W/H, the aspect ratio of the tall building. A 0.4 power law is a reasonable fit with $L/H \leqslant 1$ and $W/H \ngtr 1$; the constancy of V_A/V_a when W/H exceeds 1 suggests two-dimensional flow. It is appropriate here to add that the maximum velocity at 3 m (scale) above the ground varied by not more than about 10 % in a band 0.1 to 0.2 L wide extending laterally to between 0.5 and 0.75W, as in figure 2. A detailed comparison with one typical arrangement did not show a significant difference between values 3 and 1.5 m (scale) above the ground in this region. The effect of H/h has so far been investigated in a limited way and figure 4*c* gives a tentative view. Present indications are that $V_A/V_a \simeq 0.5$ at $H/h = 1$, i.e. there is a sheltering effect; presumably the degree of shelter depends on L/H but values of about 0.5 have been obtained with L/H as great as 6. V_A/V_a increases with H/h to a maximum and then diminishes; a value with $h = 0$ is given.

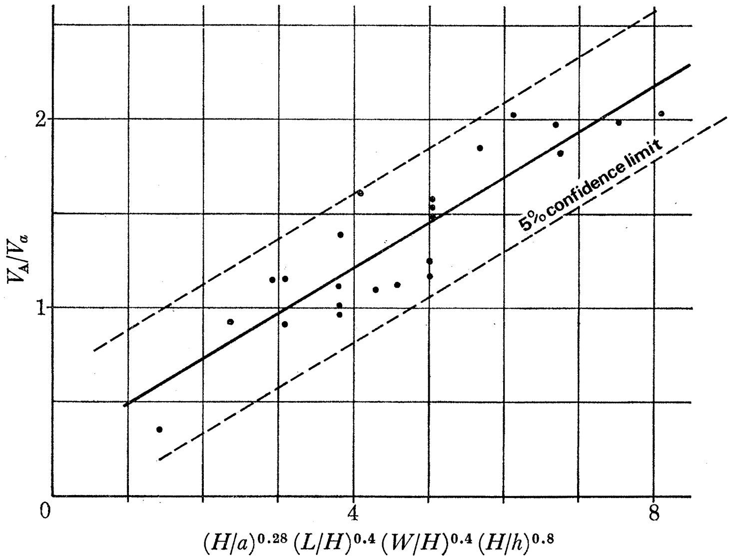

FIGURE 5. Correlation of data for stable vortex. Correlation coefficient 0.90; $p < 0.001$. $\alpha = 90°$; $H/a \ngtr 33$; $W/H \ngtr 1$; $L/H \ngtr 1$; $H/h \ngtr 8$.

In seeking to generalize, figure 5 was prepared covering provisionally the given limits within which a stable vortex has been observed. The term H/h has been tentatively given an index 0.8 for the range of conditions under consideration, with the result that H is eliminated apart from its presence in the first term. The figure includes a few points with aspect ratio greater than 1, for which W/H has been taken as 1; cf. figure 4*b*. The equation of the line shown is

$$V_A/V_a = 0.24\{1 + (H/a)^{0.28}(L/H)^{0.4}(W/H)^{0.4}(H/h)^{0.8}\}, \qquad (6)$$

or, multiplying both sides by $V_a/V_H = (a/H)^{0.28}$

$$V_{\mathrm{A}}/V_H = 0.24\{(a/H)^{0.28} + (L/H)^{0.4}(W/H)^{0.4}(H/h)^{0.8}\}. \tag{7}$$

It can readily be shown that for typical slab buildings between say 50 and 100 m high, the ratio V_{A}/V_H is roughly 0.75 for practical values of the distance between the buildings, say 30 to 50 m. In using the equations, W/H should be taken as 1 when the aspect ratio is actually greater than this.

Measurements of V_{B}/V_a have so far been done using a model equivalent to 49 m high, 12 m deep with a 12 m high building to windward. In the range $0.5 < L/H < 1.5$ with $0.5 < W/H < 1$, the ratio V_{B}/V_a was found to equal $1.96 \pm 6\,\%$; correspondingly, $V_{\mathrm{B}}/V_H = 0.91$. In length, zone B was roughly equal to the height of 49 m. Again further study is needed.

The results described have been useful in providing a quantitative basis for dealing with some practical situations. Moreover, the general flow pattern observed in the wind tunnel agrees qualitatively with observations around large buildings, with one of which an array of streamers and paper cones was used to indicate the flow. The good agreement between model and full-scale measurements of velocity along a precinct to windward of a building 75 m high by 70 m wide at Croydon was reported previously (Wise *et al.* 1965). Further results to be reported separately for a building 48 m high about 70 m downwind from two-storey houses also give fair agreement with expectations from model tests. Jones & Wilson (1968) showed a good correlation between model and full-scale results for streets with low buildings in part of Liverpool. Although much remains to be done in this field there is encouraging agreement so far, both qualitatively and quantitatively, between model and full-scale data.

Case studies

The following examples illustrate specific problems that have arisen in practice and which have been studied in wind tunnels. In the present paper it is not possible to describe the work in detail but major points are brought out and discussed in relation to the foregoing data, and remedies for windy areas are described. The model studies were generally done using existing models prepared by architects at a scale of 1/192.

(*a*) *Leeds* (*Merrion Centre*)

The architects for this £6M redevelopment project incorporating a 13-storey main slab some 45 m high (shown in figures 6 and 7) wrote to the Building Research Station in 1964. They said that in still weather, conditions in the pedestrian precinct, some 10 m wide, were much less pleasant than in the streets in the vicinity and strong winds were also amplified, making the area uncomfortable. They asked for a wind tunnel investigation which was undertaken at the Station using the site model to a scale of 1/192; blocks equivalent to buildings 4-storey high were used to represent development to the west of the site. The tests were done using a velocity gradient with 0.28 power law. Both the wind tunnel study and site observation showed the highest wind speeds—much higher than in adjacent streets—to be at points 1, 2, 3 and 4 on the plan (figure 7) and wind speeds near the centre of the slab to be lower, which is consistent with the more recent results on the idealized models. Table 1 gives typical model values and shows also the results obtained with the largest of four designs of roof over the precinct that were studied. The effect of wind orientation can be seen. For the WSW direction, the ratio of the speed at the side of the precinct (taken as the mean of that at points 1, 2, 3, and 4) to that at the top of the slab is 0.94, which is similar to expectations from the idealized models. Following the wind tunnel tests, the developers of the site decided to construct a roof over all the precinct in view of the reductions of wind speed achieved in the experiments in this case. This was difficult since the buildings had not, of course, been designed with such an eventuality in mind. The solution involved the fixing of steel angles to existing reinforced concrete beams and columns. These were used to support

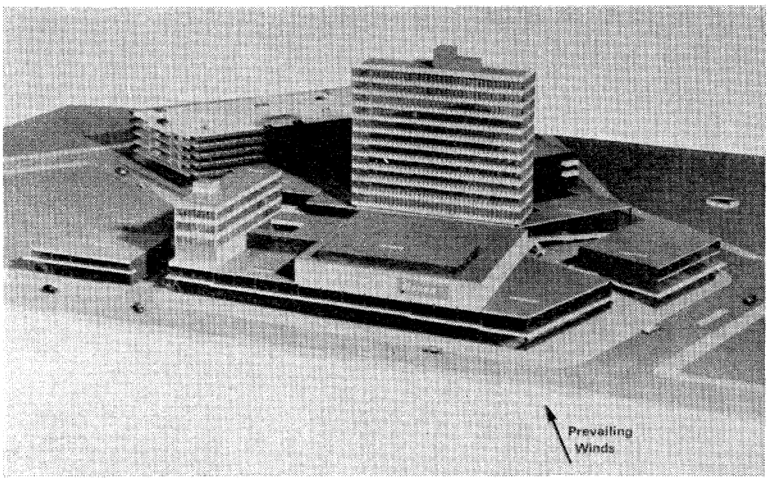

FIGURE 6 Model of the Merrion Centre.

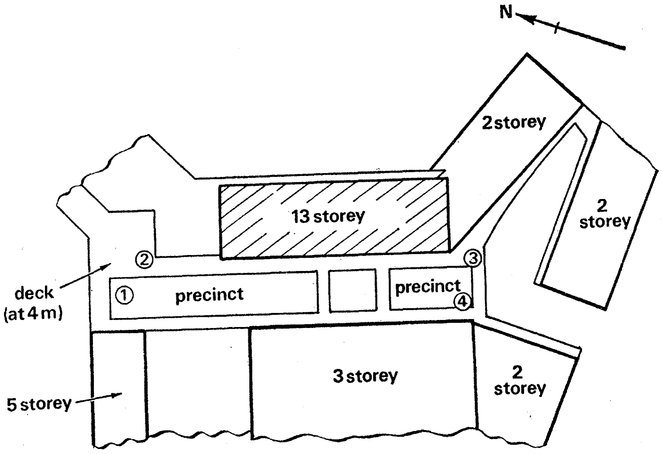

FIGURE 7. Diagram to illustrate layout at Leeds.

TABLE 1. WIND SPEED RATIOS FOR MERRION CENTRE

	measuring station				
wind direction	1	2	3	4	
WSW	0.88	0.94	1.04	0.92	as built
	0.18	0.18	0.30	0.20	with roof
SSW	0.93	1.05	0.35	0.30	as built
	0.39	0.41	0.50	0.50	with roof
WNW	0.34	0.48	1.02	1.00	as built
	0.75	0.57	0.36	0.34	with roof

Notes. Model results: stations 2 and 3 on walkway 4 m above ground. Speeds relative to that at the top of the slab.

steel beams spanning the precinct which in turn supported a steel roof deck and vaulted rooflights. The architects recently reported that this solution has provided a comfortable and pleasant environment.

(*b*) *Croydon Centre Development*

The design decisions for this development were made in the late 1950s. In 1964 the architects asked the Building Research Station for a wind-tunnel investigation of wind problems that had arisen at ground level. The layout is illustrated in figures 8 and 9, the former showing the model precinct on the west side of the slab covered by a roof, partly beamed, as finally recommended.

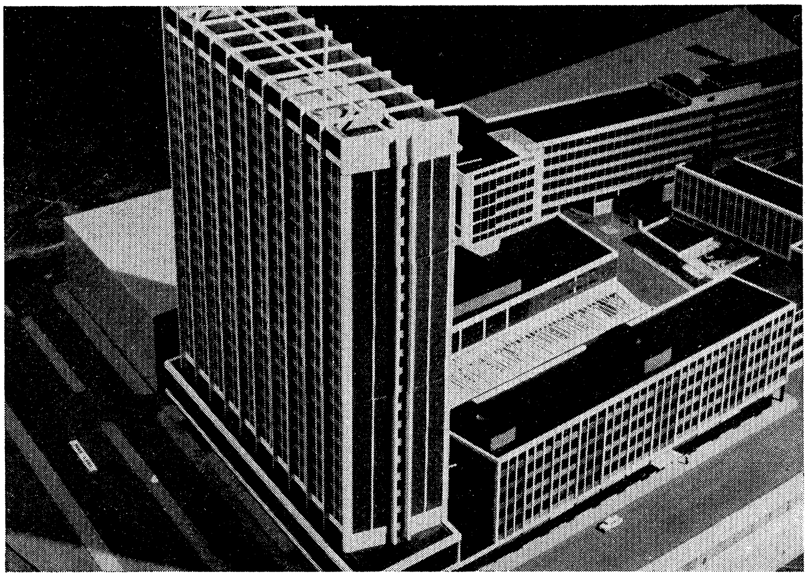

FIGURE 8. Model of part of the Croydon Centre.

The slab is about 75 m high, 70 m wide and 18 m deep; a passage 12 m wide and 4 m high beneath the slab connects the precinct with the street. An investigation similar to that for the Merrion Centre was carried out.

West winds. Both the wind-tunnel study and site measurements showed that the greatest speeds—much higher than in adjacent streets—occurred at point 4 (reverse flow) and point 1. Some values from one series of model measurements are given in table 2 from which it can be seen that, as built, the speed at point 4 was 0.68 of that at the top of the slab, the same as for a roughly similar geometry using idealized models but without the low buildings that run parallel to the precinct at Croydon.

East winds. A jet of air blows through the passage into the precinct. Speeds in the precinct are given in table 2 which shows also that, with the passage completely blocked, speeds are small on the leeside as would be expected.

Study of 20 roof designs, ranging from small canopies to complete roofs, showed that significant reductions of speed along the full length of the precinct could not be effected without an extensive roof to keep the eddy above the precinct, together with screens in the passage blocking 75 % of the area to deal with the effects of east winds. Results for one of the best designs (figure 8) are given in table 2. Owing to structural load difficulties, it was not possible to use beams over part of the precinct; the precinct is now roofed in its entirety in a vaulted fibre-glass construction, which has provided a comfortable and pleasant environment.

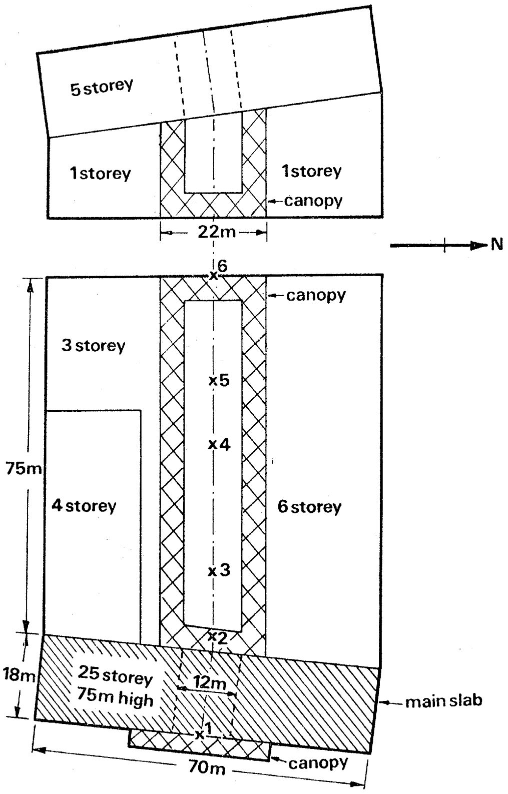

FIGURE 9. Diagram of precinct at Croydon.

TABLE 2. WIND SPEED RATIOS FOR CROYDON CENTRE

wind direction	measuring station 1	2	3	4	5	6	
W	0.72	0.36	0.49	0.68	0.64	0.53	as built
	0.40	0.19	0.23	0.28	0.19	0.23	with roof and 75% screen
E	1.0	0.83	0.74	0.70	0.60	0.55	as built
	—	0.11	0.13	—	0.13	0.36	with 100% screen
	0.59	0.53	0.47	—	0.17	0.21	with roof and 75% screen

Notes. Model results: roof as figure 8. Speeds relative to that at the top of the slab.

(*c*) *Orchard Park, Hull*

In 1966 at the request of George Wimpey & Co. Ltd a wind-tunnel investigation into environmental conditions around a group of four proposed multi-storey blocks was undertaken by the Building Research Station. The purpose of the inquiry was first to find out if the layout of the group could be amended with advantage, and secondly to collect information relevant to the design of other clusters. The proposed layout is shown in figure 10; pedestrian tunnels penetrated both the 8- and 22-storey blocks from north to south. The tests were done as already described, with flow visualization and a series of velocity measurements at 18 points around the site for five wind directions, including the prevailing direction at Hull of southwest. The model was constructed so that block heights could be reduced to 8 storeys and a gap between the 13- and 22-storey buildings could be varied. The work confirmed that extensive windy areas were likely with velocity ratios at 2 m of up to 1.9; there was a horizontal eddy in the courtyard, and high velocities in the pedestrian tunnels, with a ratio of 2.1 at one exit. In the meantime the architects and contractor had provisionally agreed to build the cluster as three completely separated blocks of 17, 19 and 22 storeys and the most valuable result of the test was that it enabled a decision to be reached to avoid the close grouping in figure 10. Information from the model tests also showed that reducing the heights improved conditions considerably but introducing varying gaps between the blocks gave benefits in some respects and disadvantages in others.

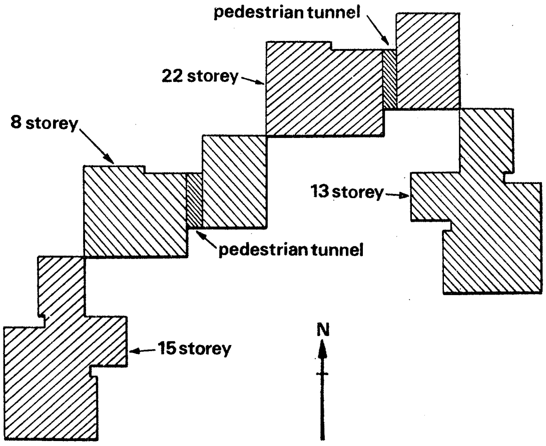

Figure 10. Diagram to illustrate a proposed layout at Hull.

(*d*) *Corby Town Centre*

An investigation in the open jet tunnel at the National Physical Laboratory of air flow in a model of Corby Town Centre was described by White (1968). The model to a scale of 1/128 was tested in a velocity gradient to a 1/7 power law, formed using a slatted screen. A plan of the proposed layout is given in figure 11. It shows an 18-storey slab—about 55 m high— surrounded by buildings of 3 or 4 storeys, except on the west which was open and to be developed with low buildings later. Table 3 gives spot values for the prevailing southwest winds (45° to the slab) converted from the readings given by White to the ratios used in the present paper. The observations agree broadly with what has already been described. Windy points occurred in front of the slab (station 4) and somewhat higher speeds in the zones beyond the points of separation (stations 6, and 1 and 2). Results for the slab of the Merrion Centre with a SSW (45°) wind provide the nearest comparable values available from B.R.S. work; the values of 1.1 for the side of the Corby slab are about 10 % different from that for the roughly similar positions in table 1. Differences in detail and in the power law used are presumably contributory factors, the effects of which could only be resolved by more detailed investigation. Some screening and canopies were tried for Corby to reduce speeds but these were unsuccessful and the final recommendation adopted by the architects was to provide equal accommodation in four floors instead of eighteen.

(*e*) *General comments*

Of the large number of inquiries received at the Building Research Station, 20 have been clearcut enough to examine in more detail. Six concerned completed sites where windy conditions were being experienced. Two are described in the foregoing, and were regarded by the developers as being sufficiently serious to warrant the roofing of the precincts concerned. It was considered that some of the shops were left untenanted on account of the windy environment which discouraged shoppers. In three of the other existing situations the slab buildings were lower and the problem was not regarded as sufficiently serious to warrant the cost of a roof. Difficulties in supporting a roof, its appearance, lighting problems, and the need to provide alternative access for fire engines are among the problems faced when existing sites are to be improved in this way. The sixth existing case was solved by adopting the recommendation of a light-weight enclosure about a pedestrian way. It is worth emphasizing that small canopies and screens have not in general proved sufficient to make a worthwhile improvement in conditions.

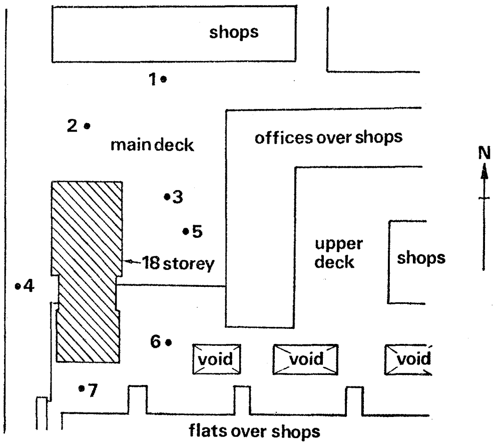

FIGURE 11. Diagram to illustrate Corby Centre (White 1968). The shaded block is 18 storeys high.

TABLE 3. WIND SPEED RATIOS FOR PROPOSED CORBY TOWN CENTRE

(Based on White 1968.)

measuring station							
1	2	3	4	5	6	7	ratio
1.7	1.7	0.4	1.4	0.4	1.9	0.9	at 3 m
1.1	1.1	0.3	0.9	0.3	1.2	0.6	to top of slab

Notes. Model results; SW wind.

As noted earlier, wind speeds in these practical cases were much higher than in adjacent streets. It is not possible at model scale to get an adequate measure of the maximum speeds relative to those in the streets without a very extensive model. Site measurements give some idea of this relationship, but the idealized results have also helped in this respect. The results for parallel buildings each 12 m high at right angles to the flow indicate a measure of shelter between them—velocity about half of that in the free stream at the same height—and a tall building from this information may thus give values up to some 4 times that between the low buildings. The figure for the low buildings probably represents better than the free wind speed what is commonly experienced in towns.

Some inquiries concerning proposed developments were received when it was too late to alter layout and design of buildings, in which case roofing or screening appropriate areas was considered. Sometimes it was possible to alter the layout and design of the buildings and in one or two cases this has been done, either from a wind tunnel test or by using the idealized data.

Recommendations to improve wind environment may well conflict with other aspects of planning and design. For example, providing equal accommodation in lower buildings requires a greater site coverage which may affect such diverse matters as access and daylight. The designer may thus have to try and weigh the benefits of improved wind environment against a possible loss in some other direction, and an enclosed precinct planned into the scheme from the outset may well be the most attractive solution. Various developments of this kind are planned in the U.K.

Finally it should be emphasized that openings and passages into precincts that are placed beneath tall slab buildings are likely to form wind tunnels as described in the Croydon case, for which a screen was necessary. Among other examples are a town centre in Bracknell tested at the University of Leicester (A. C. Tory 1969, personal communication) in which speeds within the passage approached twice that of the free wind at the same height, and a screen was recommended. The writer observed the same effect in a large redevelopment with a 50-storey tower in Boston, U.S.A. in which it has now been found necessary to enclose some of the pedestrian arcades as protection against the effects of winds.

Design information

The information from wind tunnel studies of the kind described supported by field data may be used to develop generalized charts from which designers can assess the order of wind speeds likely in schemes on the drawing board. A publication on these lines is to be written at the Building Research Station, drawing on all the information now available, and experience suggests that its use should often be sufficient as a basis from which to predict the major trouble spots and suggest solutions for particular developments. Wind-tunnel studies will still be necessary in unusual and especially complex situations.

Design criteria and meteorological data, especially on the frequency of wind speeds of different magnitudes and related temperatures, are also needed for design purposes. Shellard (1968) has assembled meteorological data. The design criteria may involve both thermal comfort of the pedestrian and mechanical effects such as the buffeting of clothing and umbrellas and the raising of rubbish. The Beaufort scale gives the following guidance:

4: 5 to 8 m/s—raises dust and loose paper; small branches are moved.

6: 11 to 14 m/s—large branches in motion; umbrellas used with difficulty.

A study of a few subjects in the wind tunnel has been done at the Building Research Station to supplement the information on mechanical aspects and this work suggests that wind speeds much above about 5 m/s are likely to give unpleasant disturbance to clothing and hair. Measurements by Chepil (1945) suggest that a maximum of 5 m/s is a reasonable value to use if dust particles are not to be set in motion.

As regards thermal comfort, the wind chill index of Siple & Passel (1945) is an example of results from many studies of requirements for Arctic conditions which are hardly applicable in the U.K. The heat balance equation for a human body which has been used by several workers in this field and recently during research at the Building Research Station on thermal comfort indoors may be applied to conditions outdoors, for example, to determine criteria for a man or woman strolling around a shopping centre. Making reasonable assumptions about metabolic rate, and the thermal resistance of body layers and clothing, speeds of some 5 m/s appeared tolerable at 10 °C in normal winter clothing. No account has, of course, been taken in this exploratory calculation of the time spent outdoors.

CONCLUSION

The architect and planner need meteorological information and comfort criteria as well as aerodynamic data for the design and layout of groups of buildings in towns. Meteorological information is available but it does not always relate as closely as may be desired to urban situations and there is a need to build up new data in this area for use in urban design. Comfort criteria, also, are lacking but the figures given in the paper provide a rough basis for design.

On the aerodynamic side, the correlations and data given provide the designer with a tool that has not so far been available. The presentation of this information in a form suitable for design use is receiving attention. More work of course could well be done in this field. The correlation given may well be refined by further detailed studies, and the effect of such factors as wind orientation, different velocity profiles and possible Reynolds number effects with deeper buildings all merit investigation in wind tunnels. Further comparisons of model and full-scale data are also needed. Furthermore, the work so far has been concerned with mean velocities and the effect of turbulence should be considered in the long term. A broad approach of this nature is likely to be of benefit eventually to a range of problems in building design. As far as wind environment is concerned, however, it would be a pity if aerodynamic knowledge outstripped that on human requirements and meteorological aspects. Work in these two fields is also needed.

The work described forms part of the research programme of the Building Research Station of the Department of the Environment and this paper is published by permission of the Director. The experimental work was carried out by D. E. Sexton (in charge), A. D. Penwarden and P. F. Grigg. The author wishes to acknowledge helpful discussion of the draft with colleagues.

Illustrations of urban centres are reproduced by kind permission of Gillinson, Barnett and Partners (Merrion Centre), Ronald Ward and Partners (Croydon Centre) and George Wimpey and Co. Ltd (Orchard Park).

NOMENCLATURE

V_a	mean velocity in free airstream, at height a above ground
V_H	mean velocity in free airstream, at height H above ground
V_A	maximum velocity on centre line in zone A, at height a above ground
V_B	maximum velocity in zone B, at height a above ground
C_p	dimensionless coefficient for stagnation pressure on the tall building (figure 2)
c_p	dimensionless coefficient for pressure on rear face of low building (figure 2)
H	height of tall building (m)
W	width of tall building (m)
D	depth of tall building (m)
L	distance between tall and low building (m)
h	height of low building (m)
ν	kinematic viscosity of air (m^2/s)
α	angle of the airstream to the face of a building (degrees)

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DISCUSSION

D. E. SEXTON (*Building Research Station*)

At the outset of the B.R.S. work it was decided to make selected measurements at full scale to compare with the results of wind tunnel investigations. Experimental difficulties made progress slow but several sets of measurements were made. With a few large buildings portable cup anemometers, mounted on stands 3 m high, were used to measure mean wind speeds around the buildings. The related free stream speed was generally measured with a similar anemometer, carried on a 12 m high portable mast, located so as to give the best possible exposure. In one study on the B.R.S. site the free stream speed at the meteorological area on the site, at an effective height of 15 m and 240 m away from the building studied, was used as a basis for comparison. In the earliest study, at Croydon, wind speed in the precinct was determined with a vane anemometer hand-held at 2 m. Since it proved impossible to obtain a reliable local measurement of the free stream speed, the results in this case were related to the measured speed at one

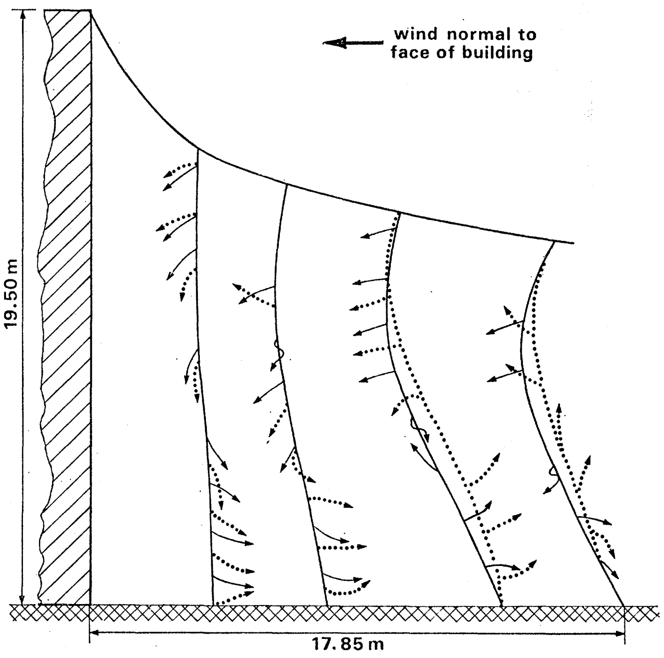

FIGURE 12. Flow pattern to windward of a laboratory building.

end of the precinct. A 3 min sampling period was used in all studies. The ratio V_A/V_H was determined from the results of the measurements. The value of V_H to use in this ratio was found from the free stream measurements assuming that the variation of speed with height was according to a power law of exponent 0.28.

Figure 12 shows the flow pattern indicated by streamers to windward of a building on the B.R.S. site 19 m high and 40 m wide on two occasions when a moderate wind was blowing normal to the face of the building. The downward flow near the face of the building and the vortex to windward show clearly (c.f figures 1 and 2). The wind speed was measured simultaneously at various points in the plane of the streamers at 3 m above ground level with the following results:

distance from building/m ≈	3	9	16	24	30	37
V_A/V_H	0.57	0.64	0.60	0.37	0.30	0.30

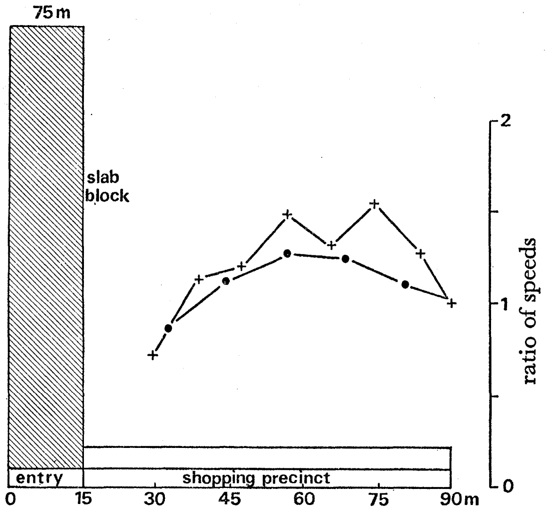

Figure 13. Wind speed in the Croydon Centre precinct. Speeds are expressed as a ratio of that at the end of the precinct. ●, wind tunnel; +, site.

The nearest building to windward was 7 m high and 105 m away; there were a few small trees about 7 m high in the intervening space. In this case there is no direct comparison with an identical model, but the values of this ratio are of the order expected from the model investigations. Figure 13 compares the results of model and full-scale measurements at Croydon and shows an encouraging measure of agreement. The results given in figure 14 relate to multi-storey flats in a typical London suburb; they were in a block 48 m high by 33 wide by 15 m deep, approximately 70 m downwind of two-storey houses about 9 m high. Recent experiments with an idealized model of similar W/H, with $L/H = 1.33$ and $H/h = 6$ (compared to 1.46 and 5.3 respectively for the actual building), gave a maximum value of V_A/V_H of 0.5. Again there is reasonable agreement between model and full scale.

D. J. W. Richards (*C.E.R.L. Leatherhead*)

There are two common criticisms of aerodynamic investigations, namely their duration and cost. The duration of aerodynamic investigations is related to their nature and scope. Since wind-tunnel tests are usually involved, the design and construction of the model is often the most lengthy part of the investigation. At C.E.R.L. a number of wind tunnel models have been designed and constructed. Among these some eight site models, approximately 5 m square, have been built, and have involved the construction of the landscape and the buildings as well as the structure of interest. These models were constructed over a three-year period, during which the time taken to construct them has been halved by the use of machine tools and simplified manufacturing processes. Currently, the most significant factor in such aerodynamic investigations is the time taken to obtain the information necessary to construct the model. It may be concluded that the duration of aerodynamic investigations can be reduced by experience, in the case of construction of the models, and by effective collaboration between the designer and the aerodynamicist during the design stages of the model and the experiment. In the latter context it is very desirable that the designer specifies those parameters which are fixed and those which can be changed or adjusted as a result of the aerodynamic investigation.

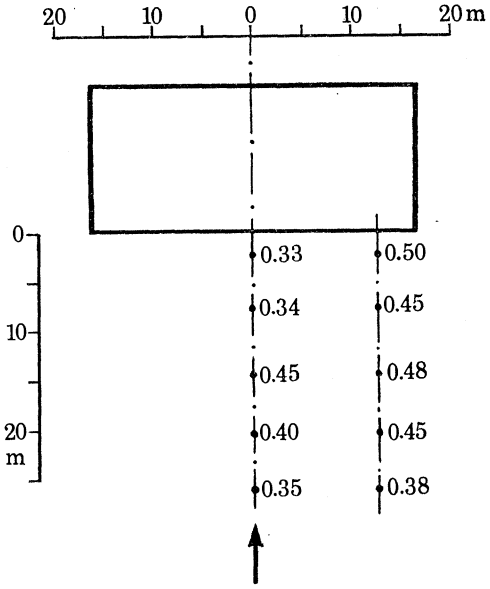

FIGURE 14. V/V_H near a building 48 m high (V is the velocity at height 3 m above ground).

The cost of aerodynamic investigations is again related to their nature and scope. When such costs are considered by a designer, the total benefits accruing from the work must be considered. In particular the cost of the aerodynamic investigation should not be related only to the construction cost of that part of the structure involved, but should include the on-costs which can be very expensive if the aerodynamic performance of a part of a structure is unsatisfactory. For example, the cost of the evaluation of wind speeds in a shopping precinct should not only be related to the cost of wind baffles, wind canopies, etc., but also to the loss of sales in such shops due to intolerable environmental conditions.

It is concluded that the duration and costs of aerodynamic investigations will decrease as more studies are carried out and more experience is gained and that the value of such investigations will be enhanced by effective collaboration between the designer of a structure and the aerodynamicist carrying out the investigation.

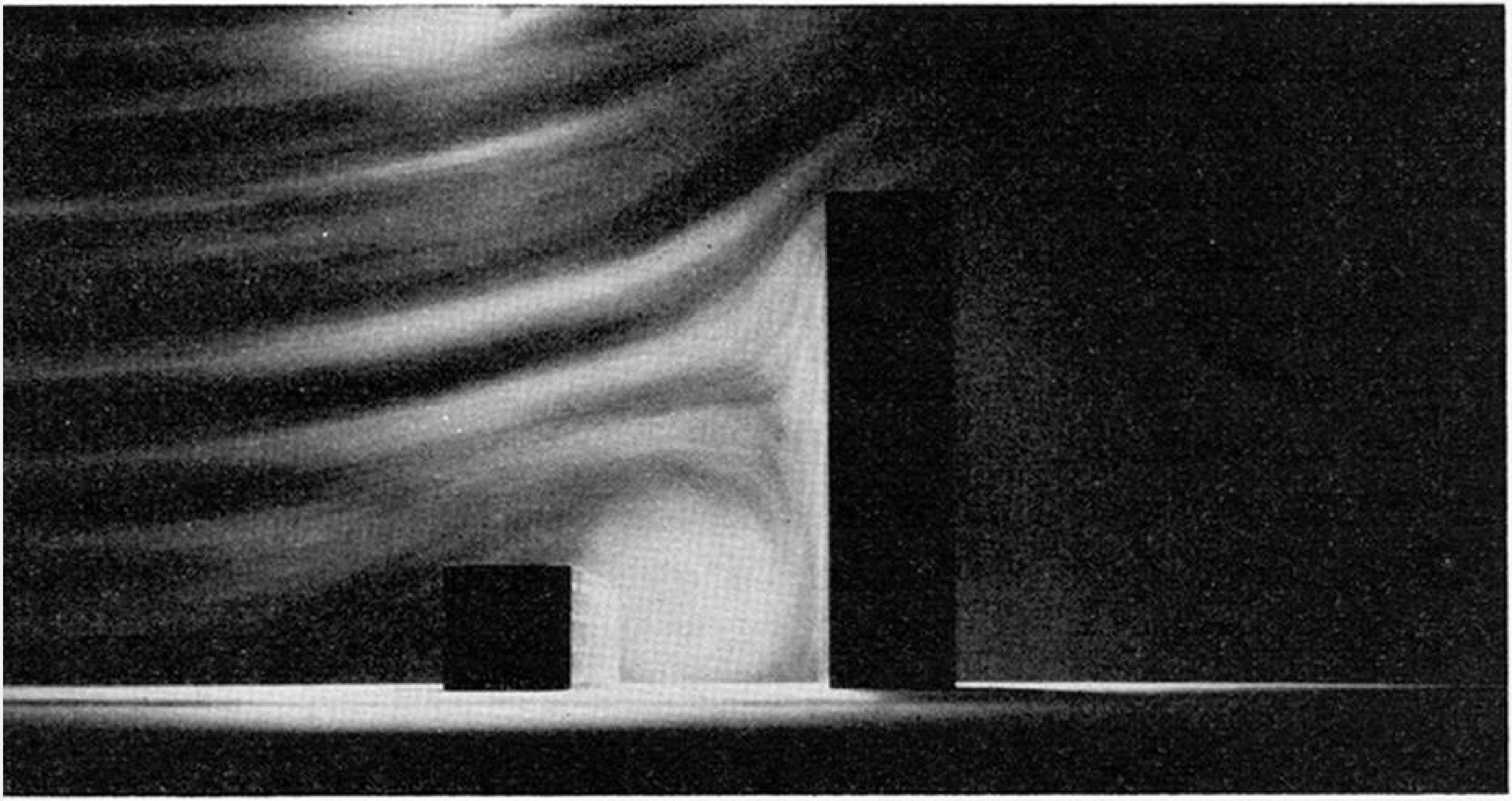

FIGURE 1. Flow pattern.

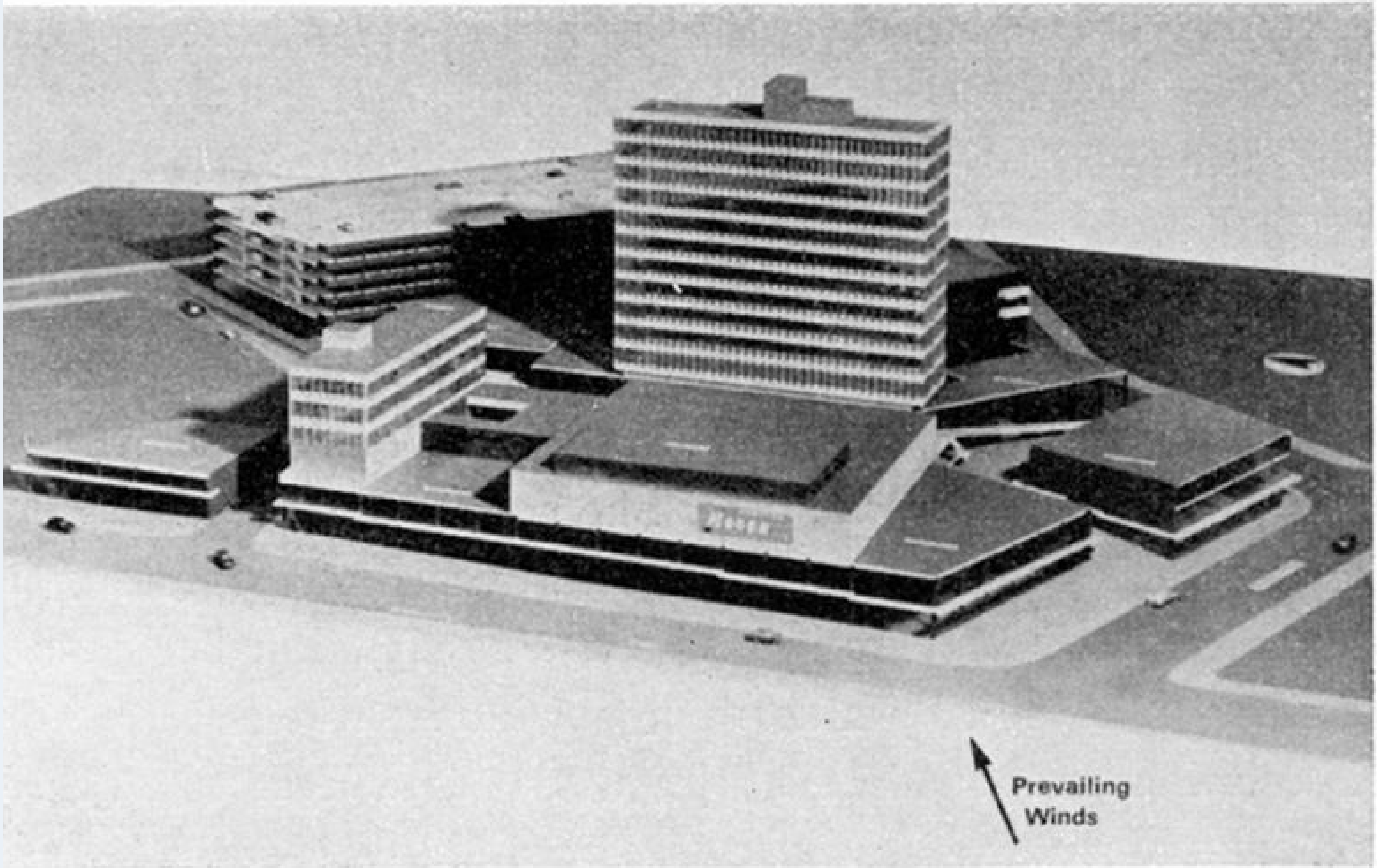

FIGURE 6 Model of the Merrion Centre.

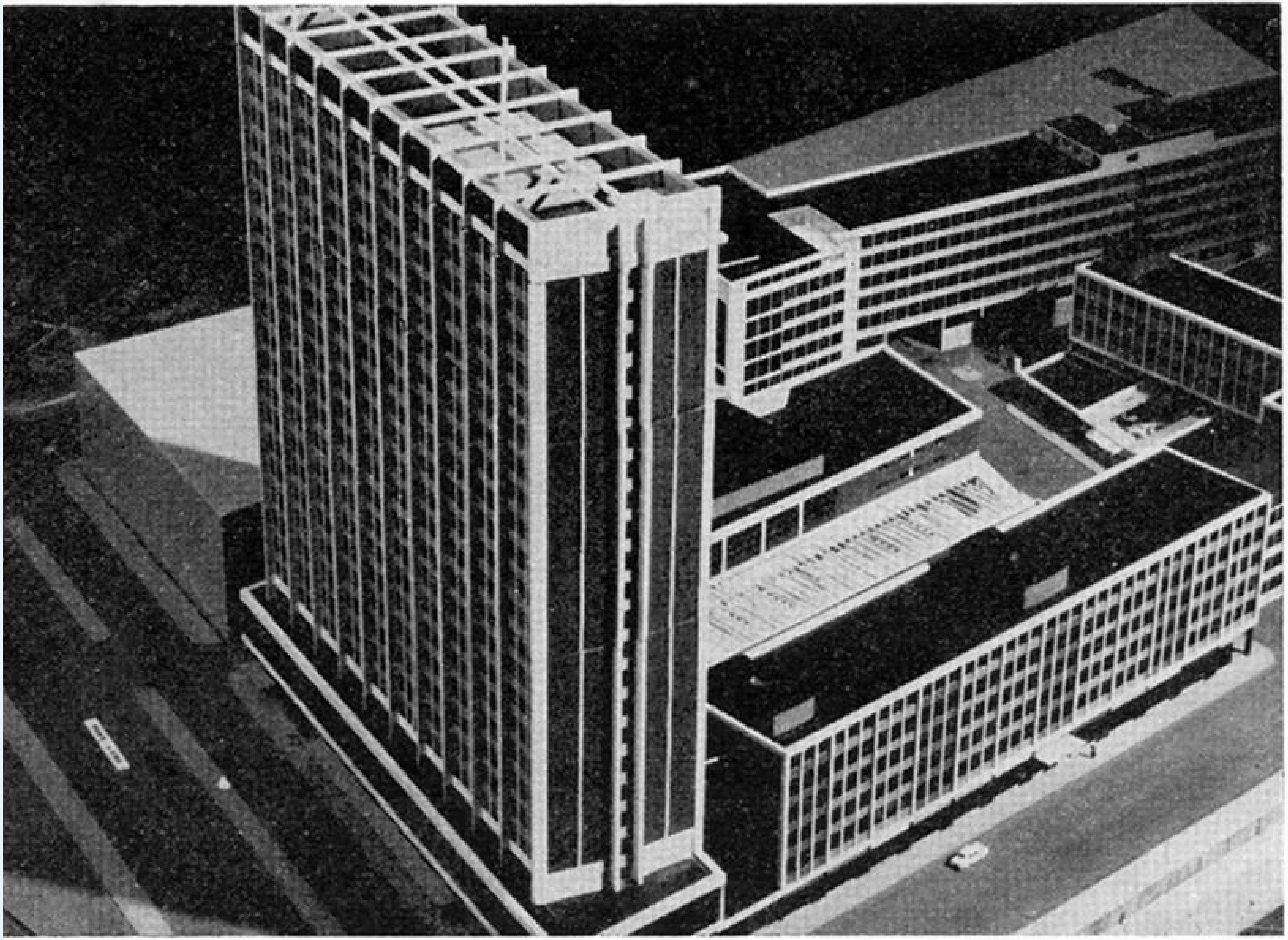

FIGURE 8. Model of part of the Croydon Centre.