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Landscape effects with particular reference to urban situations

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It is probable that the sites of most early settlements were determined by the need for water, so that villages and towns began, for the most part, in valleys where problems of wind effects were not severe and the structures themselves not of a form or dimension which would seriously accentuate wind effects. But as these settlements grew, for reasons which are not our concern here, they spilled out over surrounding hills; moreover, in recent years the steel framed or reinforced concrete building has presented a fashionable alternative to the traditional stone or brick construction. As a result, we have a comparatively new problem; the interaction of groups of buildings of new forms with the natural landscape in modifying the structure of the natural wind. I have been asked to talk about this new problem.

How to define the wind

Before being able to describe the effects of an urban environment on the wind, we must decide the qualities which define the wind. An obvious starting point is to define mean wind speed and mean direction, even though the wind is far from steady either in magnitude or direction. It is known that the mean wind speed changes with height in both magnitude and direction, so a mean velocity profile and spiral can be defined. However, the mean wind speed is not enough; we require also to define the turbulence superimposed on the mean. This, in turn, requires measurement of magnitude and frequency in each of three directions. The magnitude can be presented either as a root mean square velocity or as a standard deviation from the mean; but since large gusts are less frequent than small eddies, it is often convenient to express the distribution of energy by power spectral analysis. Auto- or cross-correlations present some of this information in a slightly different way and also add to it.

What is the architect interested in doing? He wants to ensure the comfort of human beings in and around the buildings with which he is concerned, and in particular on pedestrian walkways, leisure areas such as courtyards, and in roadways. He is concerned with the wind loads on his buildings, from the safety standpoint, both of the main structure and of the cladding. He is interested in ventilation, either natural or forced, of his buildings and car parks, and in the efficient performance of his chimneys and other means of effluent disposal. In all these matters he must be as much concerned with the effect of his building on its surroundings, as he is in the effect of the surroundings on his building: it is the combined effect which matters.

What information about the wind does the architect need to allow him to do his job properly? We will consider each aspect in turn and try to decide what is necessary. As far as the reactions of pedestrians are concerned, we know little except that gust speed, coupled with temperature and humidity, will be involved. For the cyclist, gusts occurring for periods of less than a second are troublesome and for many other outdoor activities different criteria could be paramount. It would be valuable for a research programme to establish, in numerical terms, what the criteria are.

Turning now to the structure of the building and in particular to the cladding, it is important that the architect should know the maximum wind pressure occurring, say, once in 50 years and lasting at least 3 s, since this is likely to prove to be the design case. Any part of the structure or cladding which is liable to oscillate should be dealt with separately. To calculate the loading on the structure, the maximum pressures over a slightly longer period (up to 15 s for larger buildings) are required, but it is now important to know how the local wind vectors are correlated. It must always be remembered that turbulence at certain frequencies is often produced by the building itself, even though there is little energy at that frequency in the approaching airstream.

It will have become clear that the description of the wind structure which will allow the architect to satisfy all his design requirements falls far short of a complete description. Yet a complete description is necessary for the meteorologist and the aerodynamicist, attempting to simulate natural conditions in the wind tunnel, to agree on the accuracy of the representation.

URBAN AREAS

How does the wind in an urban area differ from that over a flat plain? In general, the mean wind speed and low-frequency turbulence are caused by synoptic conditions with effects deriving from sun and cloud cover. The mean velocity profile and the medium and high-frequency turbulence are produced by the surface of the earth. Dr Pasquill has dealt with the first, which applies generally to both open and urban areas; I want to consider now the boundary layer produced by the surface of the earth. Since G. I. Taylor presented his paper to this Society in 1915, the planetary boundary layer involving the wind spiral or the approach to the geostrophic wind has been studied by many authors.

In 1958 Elliott studied the problem of the flow above a change of roughness, to be followed by Panofsky & Townsend in 1964, Townsend himself in 1966 and, among others, P. A. Taylor in 1967. All used assumed forms for velocity or shear stress profiles within an internal boundary layer developing downstream of the roughness change. In the rest of my paper I will refer to the initial boundary layer as the over the ground approaching the feature or urban area, and to the internal boundary layer as that produced by the local roughness elements and stretching from the top of the roughness elements until it merges into the initial boundary layer. The height at which this merger takes place will increase with distance into the urban area. Nickerson (1968) and Taylor (1969) have considered the same problem numerically, Nickerson considering a step change in surface shear stress and P. A. Taylor a step change in surface roughness. Taylor concludes, among other things, that a very long fetch is required for equilibrium flow to exist above the new downwind surface. In particular, the surface wind direction adjusts only slowly to the new conditions. Petersen (1969), with the hypothesis that horizontal shear stress is proportional to the turbulent energy, uses a numerical approach to the solution of the equations and, together with other conclusions, states that this predicts transition velocity profiles which differ most clearly from other workers in that they contain an inflexion point, which he claims to be confirmed by some recent experimental data. Conditions in which there is a step change in surface temperature or heat flux (for example, the land–water transition due to different solar heating) have been examined by the same techniques. The general conclusion, with numbers suggested by Petersen, is that the fetch is to be about 100 times the thickness of the layer for the layer to be considered in equilibrium.

But in all this work uniform homogeneous roughness is assumed and the results do not apply at heights of the order of the roughness elements. Although valuable work, these results can only be applied to buildings which stand out above their neighbours. For this class of building, the work of these theorists, together with the work described by Dr Hunt and Mr Wise on isolated buildings, gives results which agree closely with available full-scale measurements. I will refer to this type of building again in the section on full-scale interpretation of wind tunnel results.

For the other type of building, that which is of a similar height to its neighbours, this theoretical work has nothing to offer. The question which research work, and probably experimental work, has to answer is the relative extent to which the wind within the roughness elements is influenced by its history and its immediate surroundings. It could be, and here I am guessing, that after the wind has travelled a distance into an ordinary estate of similar houses to envelop three houses in the wind direction, then on the ground and in the air up to the height of the roofs of the houses, the wind structure is completely governed by the estate in everything except the magnitude of the mean wind speed which is controlled by the shear layer above the houses. The distance of penetration required to lose the wind its history is an urgent matter for research and I am sure that many places, including Bristol, are working on this problem.

Mention has been made earlier of the effect of a change of surface temperature and the water–land transition quoted as an example. It should not be forgotten that grass–concrete and many other possible combinations exist in landscapes and urban environments and pose similar problems.

Practical full-scale investigations

To understand these problems we need some practical full-scale measurements of the wind approaching over variable country and flowing through urban environments. This is a very difficult and expensive experiment to carry out even once, let along many times; so it is essential that we develop the wind tunnel, together with suitable techniques, to allow model experiments to be carried out. The reasons why wind-tunnel experiments in the past have given incorrect results, with subsequent data being viewed with suspicion, are dealt with in the next section. However, for the wind tunnel to prove itself, there must be some sophisticated full-scale experiments available with which comparisons can be made and techniques proved. The Building Research Station in this country is at the forefront of such experiments, and their new experiment at Aylesbury deserves detailed mention here. Pressure measurements will be taken on the walls and roofs of seven houses in an estate. They are terraced, two-storey buildings with a $22\frac{1}{4}°$ pitch roof. The outer houses of the estate face open level country, while others will be in sheltered positions. Wind speeds will be measured at three heights on the outskirts of the estate, at various points between the houses and in many other estates. An experimental building, which will allow the measurement of loads as well as pressures on the roof and the whole building, is also being constructed on the estate. Height, roof angle and permeability can be changed in this building during the experiment, which is designed to gather the information with which wind-tunnel tests can be compared. In 1965 Professor Wilson carried out a simpler experiment in which wind speeds were measured in the centre of Liverpool, but because of the instrumentation then available, his experiment was not as complex. However, it marked the start of this type of full-scale investigation.

Full-scale investigations have been carried out on tower blocks in an urban setting; for example, those by B.R.S. on Royex House and the G.P.O. Tower in London. The emphasis in both these experiments was the effect of the wind on the building, but the G.P.O. Tower experiment in particular produced much useful information about the ambient wind.

One of the proposals for the International Field Year for the Great Lakes is to instrument the wind flowing from Lake Ontario for the first kilometre inland. This will give full-scale results of a sudden change of temperature affecting the internal boundary layer and can be used to compare with theoretical solutions. Modelling temperature changes in the wind tunnel is difficult, as will be explained in the next section, but can be done if essential.

Akin to an estate of houses is a plantation of trees and a fascinating experiment has been carried out by Byass and Randall of the National Institute of Agricultural Engineering, in which they measured wind profiles in an orchard of fruit trees in leafless and full foliage conditions.

Wind-tunnel investigations

Because of the cost, inconvenience and even the sheer impossibility of conducting full-scale experiments while buildings or estates are in the design phase, the wind tunnel must be proved as an effective means of predicting accurately the wind on and around buildings.

The wind tunnel was conceived to carry out research on models of aircraft which, except for short periods during take-off and landing and in the vicinity of storms and patches of clear air turbulence, fly mostly in uniform conditions. Wind tunnels were devised to produce an airstream of constant velocity and low turbulence, and developed over the years to produce an even more constant velocity with still less turbulence.

The planetary boundary layer, on the other hand, has a velocity profile which extends over a height of several hundred metres coupled with a considerable quantity of turbulence, the spectrum of which includes some energy at very long wavelengths. The wind tunnel adapted for architectural aerodynamics has to be different in several important respects from the wind tunnel for aircraft aerodynamics. In the past, because any results were better than none, models of buildings and sites were tested in an 'aircraft' type tunnel and because the results bore poor resemblance to full-scale results, the wind tunnel fell into disrepute.

The question to be answered is 'What are the important parameters which have to be modelled in the wind tunnel?' Early experimenters modified their tunnels to give a velocity profile roughly similar to that of the planetary boundary layer in place of a constant velocity, and produced results which were appreciably closer to full scale. Turbulence was added, measured only by its intensity, and it was found to be important in that wind-tunnel results with turbulence differed from those without turbulence, there being too few full-scale results available where the turbulence level in the wind was known accurately, for comparison to be made with full scale. But the turbulence introduced was sadly lacking at the low frequency (large eddy size) end of the spectrum. Experiments are in hand at Bristol, among other places, to establish the importance of the correct spectrum of turbulence.

There are many ways of introducing both turbulence and mean velocity profile: one solution would be to have an extremely long wind tunnel, so that the neighbourhood for a sufficient distance upstream could be modelled to produce the correct internal boundary layer. Even so, this cannot allow for contouring unless the model is to be extremely expensive, and even then the effects of phenomena-like mountain waves would not be included. Davenport favours this method at Western Ontario and Jensen and Franck in Denmark grow their boundary layers by scattering roughness elements from the intake of the wind tunnel. Grids can be used which will produce the correct range of frequencies, together with (or as part of) grids to produce the velocity profile; the grids producing turbulence modifying the velocity profile considerably. I am becoming convinced that the best way to produce the desired combination is to use a step on the floor to give the required momentum deficit together with some form of turbulence producer. This type of generation was pioneered by Counihan and Armitt at the C.E.R.L. who produced turbulence by semi-elliptic half wings attached to the tunnel floor.

Personally, I am convinced that the correct philosophy is that models should be simple and cheap and the wind tunnel and instrumentation as sophisticated as necessary to represent conditions with sufficient accuracy. The size of the model of the building and its surroundings is basically governed by the size of the wind tunnel available: however, too large a model makes the boundary layer difficult to represent and too small a model produces undesirably small Reynolds numbers. (In the case of pollution studies, with too small a model it is sometimes impossible to maintain a turbulent boundary layer over the ground.) For these reasons I prefer scales to be between 1/100 and 1/600. Wind-tunnel research, coupled with the proposed B.R.S. experiment at Aylesbury and the work of Randall in orchards, should define the area of the surroundings which must be included in the wind-tunnel model. For a model of sufficient extent, I am of the opinion that the details of the approaching airstream become relatively unimportant, save only that they resemble those of the atmosphere. A Research programme to establish the requirements of the approaching airstream would be extremely valuable.

For buildings which extend some distance above their neighbours the requirements are different. Here the velocity profile needs to be a combination of the initial boundary layer and the internal boundary layer produced by the surrounding urban area. Baines, in 1962, compared flow pictures on a tall building in a constant velocity flow with those for a natural velocity profile and showed that there was a fundamental difference, but Penwarden at B.R.S. has recently stated that with a velocity profile of the type $u/U = (y/\delta)^n$, the value of n, provided it was not zero, had little effect upon his measured pressures on a wind-tunnel model of Royex House in its built-up surroundings.

The representation of temperature gradients in a wind tunnel is difficult, although it has been done in several research programmes. Fortunately, extreme values are usually required for wind-tunnel investigations and these are often associated with periods of high-wind speed, which in turn are associated with neutral atmospheric stability. Thus, the only real need for vertical temperature gradients in a wind tunnel occurs in the study of pollution from chimneys when low wind and inversion conditions can be important. Should the representation of the change of heat flux inputs from rural to urban situations be shown to be important, this can be modelled in the wind tunnel, although with difficulty. Personally, I would always prefer to cool one part of the model than to heat other parts, so that the equilibrium temperature in the tunnel would be reached sooner.

FULL-SCALE INTERPRETATIONS OF WIND-TUNNEL RESULTS

The Meteorological Office has produced maps, such as the one published in B.R.S. Digest no. 99, showing for the whole of the U.K., with a probability of 0.63, the maximum gust velocity likely to occur once in 50 years at a height of 10 m and lasting for 3 s. Tables (currently being revised) are provided which will allow this figure to be converted into different probabilities over different return periods and different averaging times at different heights. A meteorologist with local knowledge can add to this information facts about local topographic or synoptic features.

The wind-tunnel aerodynamicist has to determine from this velocity the velocity of the wind at points on and around the building and the pressures on the building, which is what the architect wants. Those parameters have to be satisfied which ensure that the behaviour of the wind as it flows in and around the buildings is the same in full scale as in the wind-tunnel representation. For the case of a tower block which has only a small proportion of its height in the surrounding roughness, I would suggest that the important parameters are the velocity profiles of the initial and internal boundary layers, together with the turbulence expressed as a power spectra at a given height, probably that of the top of the tower block. I would suggest that the model should be accurate as to surrounding buildings for an extent equal to $1\frac{1}{2}$ times the building height in all directions, and that between the model and the grid producing the artificial profile, blocks of the scale of smaller buildings be randomly scattered on the ground to a distance and of a density equivalent to that in full scale, or up to the grid whichever is less.

In the case of a building with height about that of its neighbours, I would suggest that the height for the velocity comparison should be within the internal boundary-layer region above the buildings. The extent of the model should be sufficient to enable the detailed buildings to define the flow below the height of the buildings (at present I favour about three complete buildings), and randomly scattered buildings should extend as before. I feel that the actual velocity profile produced by the grid is of secondary importance, providing it is of the correct type, and that the level of turbulence ought to be comparable with full scale, especially in magnitude and generally in frequency.

The velocity used for comparison is extremely important. Its position should be such that it is unaffected by the details of the ground and I have therefore suggested a position in the internal boundary layer which can be covered by the tables of B.R.S. Digest no. 99. The wind-tunnel measurement of this velocity is also extremely important, as it is to be compared to the full-scale gust wind averaged over 3 s. Because of the small size of models used (1:100 to 1:600) and because velocity scales of the order of unity are used to keep up values of Reynolds number, the time scale in the tunnel will be of the order of 10^{-2}; that is to say, the 3 s average gust is of the order of 10^{-2} s gust in the wind tunnel. It would obviously be unrealistic to equate this to a mean wind speed in the tunnel. Similarly, if the building or part of the cladding is going to react to a 3 s gust, we want to know the maximum pressure which will persist for 3 s, and here I would like to emphasize that there is no magic in the value of 3 s, except that it is the minimum period to which standard meteorological instruments will respond. If the cladding can respond to a gust of shorter duration, we should supply the maximum pressure averaged over that period. In the wind tunnel, this means being able to evaluate average values over about 10^{-2} s, which requires complex equipment but is essential to a complete understanding of the problem. The use of mean pressure coefficients and mean wind speeds in place of short-term averages presumes that the ratio of short-term pressure to mean pressure is the same as the square of the ratio of short-term approaching wind to mean wind. These can be shown to be different in most cases; for example, in the following figures. Figure 1 is a trace of wind speed at a height of 40 m in a town centre as represented in the wind tunnel. In this case the time scale is 1:300 so that the marks represent 0.01 s in the wind tunnel and 3 s full scale. According to B.R.S. Digest no. 99, the 3 s gust is 48.5 m/s, so the scale has been added. The mean wind speed over this trace is 41 m/s. Figure 2 shows traces of velocity at a point under a canopy of the building and at an adjoining point on the pavement; the scales represent once in 50-year values. The difference between the spectrum of the wind at 40 m and that on the pavement is obvious. Figure 3 shows the pressure at a point on a flat roof which has a flow pattern as illustrated by Dr Hunt. The measuring point is close to the leading apex corner. The trace is typical of a region in which the vortex from the apex of the roof is moving over the measuring point. The trace shows essentially two different values of pressure with an instantaneous switch from one to the other; a mean value would be meaningless and never occurs in practice.

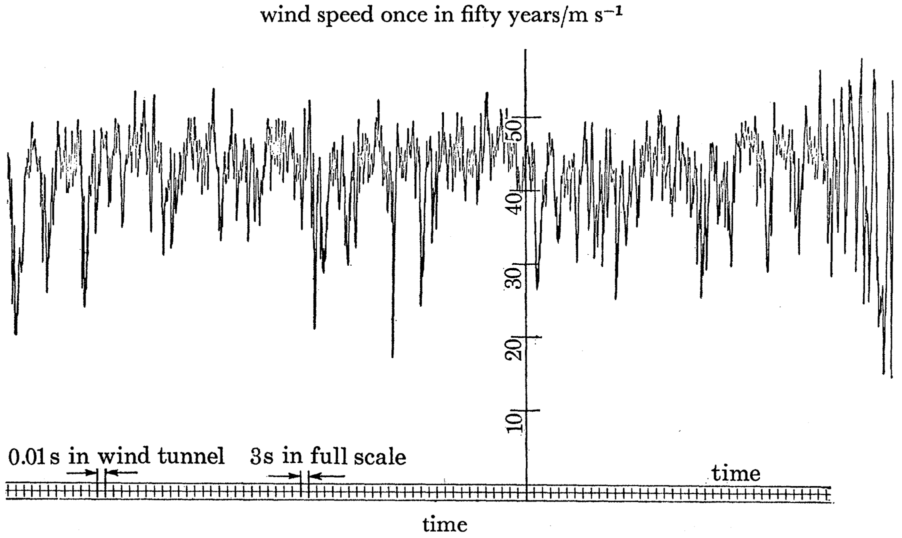

FIGURE 1. Wind-tunnel representation of wind 40 m above a town centre.

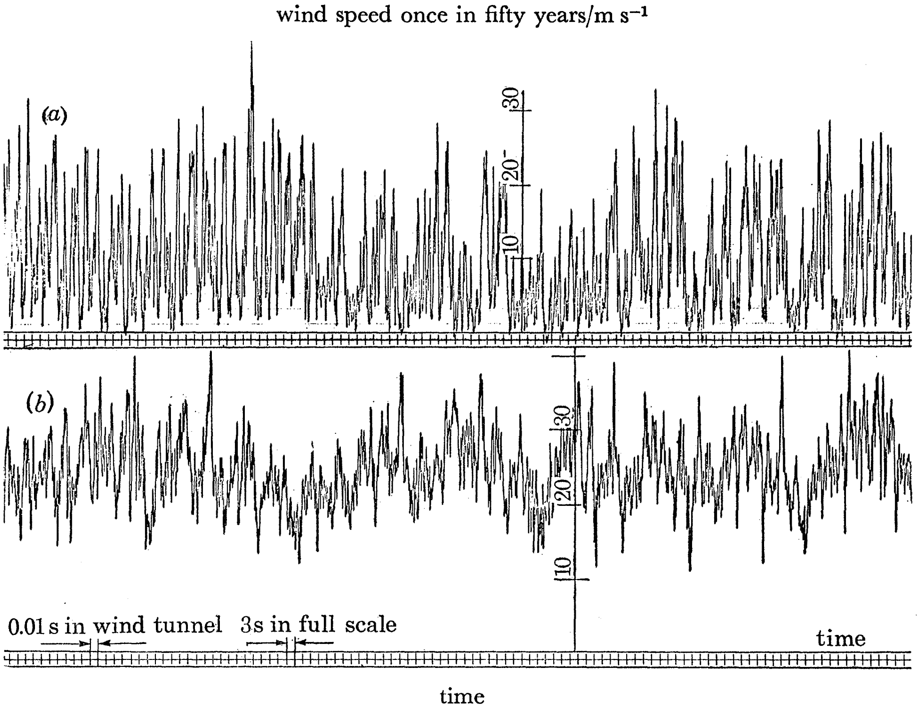

FIGURE 2. Velocity traces (*a*) under canopy of building, (*b*) at adjoining point on pavement. The same conditions apply as to figure 1.

This leads to the requirement that velocities and pressures will have to be recorded and processed automatically. If maximum occurrences persisting for only a short time have to be evaluated from a whole series of tests, sophisticated instrumentation is required. I am convinced, having used one for three years, that the first item has to be an analogue magnetic tape recorder. With current equipment in our department we have no trouble in obtaining 1800 readings a second from the wind tunnel in punched paper form, soon to become a faster service on incremental magnetic tape. A very simple program in the computer gives the maximum average for 3 s (which might be the average of 6 to 20 readings), as well as mean values and standard deviations based on any selected averaging time. The same equipment allows short-term averages to be made of pressure readings at points on buildings. One subsidiary advantage of using automatic data recording is the great saving of wind-tunnel time.

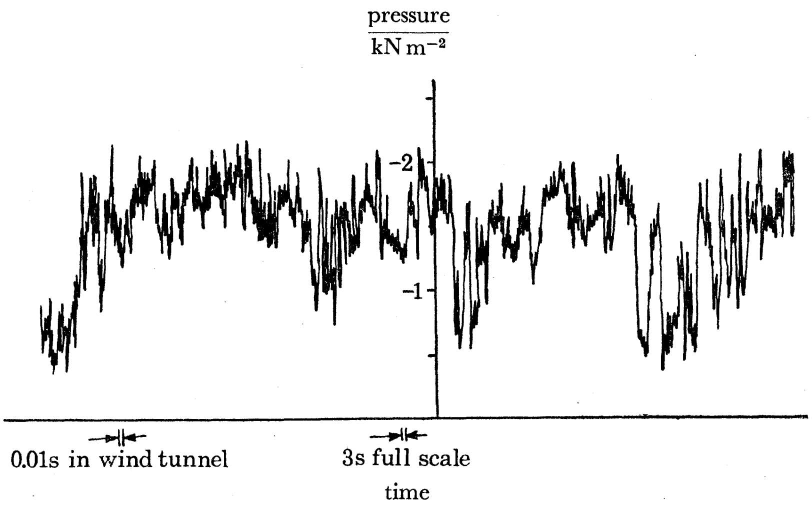

Figure 3. Pressure at a point on a flat roof over which a vortex is moving. Free-stream velocity as given by figure 1.

Conclusions

Meteorological maps are available which specify with a probability of 0.63 the magnitude of the wind defined as a 3 s gust wind speed which should be exceeded once in 50 years, at any site measured 10 m above the ground. Tables entitled 'frequency of wind velocity and direction' are available for many stations in the country on application, and payment of a fee, from the Meteorological Office. But this information is not in a form suitable for an architect, who wants to be told conditions affecting creature comfort in and around his building and also in adjoining streets, and the pressures and forces acting upon his building or parts of his building averaged over short but differing times.

To achieve this end, I believe several research programmes are urgently necessary.

(1) The wind tunnel must be established as an accurate tool for predicting the required quantities. This in turn requires the widest possible full-scale programme of measurements to provide the essential basis for comparison with wind-tunnel work.

(2) Wind-tunnel tests must establish the minimum size and extent of accurate models to be used in investigations, together with the widest tolerance of wind-tunnel velocity profile/

turbulence conditions. I stick by the principle that models which have to be made anew for each investigation should be as simple and cheap as possible, the major sophistications being in the wind tunnel and the instrumentation. In this context I welcome Report CC.662 entitled 'a standard tall building model for the comparison of simulated natural winds in a wind tunnel'.

(3) The form in which wind-tunnel information is made available to the architect and his consulting engineers needs to be correlated to their present and foreseeable needs. In particular, the quoting of maximum peak values and maximum values averaged over a range of times ought to become commonplace.

(4) Since, by the time models can be made for wind-tunnel investigations, the design is often beyond the stage when major alterations are possible, general information should be built up in data sheet form whereby fairly accurate estimates could be made by the architect in the formative stages of the design, when knowledge about wind conditions could bring about a drastic redesign.

(5) Numerical values of conditions around a building which will be considered acceptable for human beings standing, walking, cycling or playing there, should be agreed. This will require a considerable study.

I would like to express my thanks to Professor A. R. Collar, F.R.S., for his very many useful suggestions throughout the paper, to the B.R.S. for permission to mention the forthcoming Aylesbury experiment and the many colleagues on whose work I have drawn freely.