A STUDY OF THE WIND PRESSURE FORCES
ACTING ON GROUPS OF BUILDINGS

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ACKNOWLEDGEMENT

I would like to thank Dr. B. E. Lee, my Supervisor for his invaluable guidance, advice and assistance throughout every stage of the experimental work and the writing of the thesis.

I would also like to thank Dr. F. R. Fricke, who was my supervisor in the initial period of the research.

I want also to gratefully acknowledge the assistance of the Department of Building Science and Professor J. K. Page.

Special thanks are due to the members of the technical staff of the Department of Building Science, Mr. R. Webster, Mr. A. Shale, Mr. C. Hardwick, Mr. K. Holdsworth (who designed and built the electronics), Mr. R. Skelton, Mr. P. Williams, Mr. M. Broady and Mr. T. Thomas for their assistance in constructing the models used in this study.

Mrs. B. M. Wilson typed this thesis and I would like to thank her for her care and diligence with which she carried out her work.

The financial support provided by the Egyptian Government is also acknowledged.

Finally, I would like to thank my wife for her help and encouragement during the period of my research and in particular for her assistance in the writing of the thesis.

SUMMARY

A STUDY OF THE WIND PRESSURE FORCES ACTING ON GROUPS OF BUILDINGS

BAHER F. SOLIMAN

In urban areas, where buildings are mostly in groups, wind pressure forces are expected to depend on the natural wind properties as well as on the building group form. A reliable estimate of these pressure forces on buildings is necessary not only for the prediction of wind loading, but also for an accurate prediction of natural ventilation.

In an attempt to gain an understanding of the wind flow properties and the pressure forces on low rise buildings in urban areas, a detailed investigation on the interaction between the group geometry, flow properties and the resulting pressure forces has been carried out. From the review of previous work on natural ventilation, wind loading and air flow round groups of buildings, it has been concluded that no general relationship exists at present which defines this interaction. However, the similarity between boundary layer flow over rough surfaces and the natural wind on the earth's surface served to provide useful information. Considering buildings as roughness elements on the earth's surface, the geometrical and the planning parameters were investigated in order to arrive at a complete definition and the practical limits of building group forms.

In the present study, a series of model scale experiments have been performed which considered a wide range of group forms subject to two different incident flow conditions. The detailed measurements of the pressure forces on the faces of a model building situated within a variety of groups of similar form and size indicated three different trends in the behaviour of these forces. The hypothesis made, that these trends would correspond to the three flow regimes known to exist for flow over general roughness elements was substantiated by velocity profile measurements as well as by surface flow visualization tests.

Finally, the case of generalized application on buildings was investigated on the basis of the relationships obtained between group geometry, flow properties and the resulting pressure forces. Here, an alternative method for the prediction of natural ventilation in low rise buildings is presented in which the geometrical parameters defining the building group form is taken into account. It is suggested that this approach will lead to an improvement in the present methods of natural ventilation calculation.

NOMENCLATURE

A list of the nomenclature used in the thesis is given below. The list covers the nomenclature used in all Chapters apart from Chapter 4. In this Chapter the nomenclature is given within.

List of Nomenclature

Symbol	
A	Area of the intervening smooth surface/ roughness element, also site area/ building.
A_f	Frontal aspect ratio (L/H).
A_s	Side aspect ratio (W/H).
a_f	Frontal area of roughness element.
B	Constant in equation (5.2).
B_1	Constant in equation (5.23).
B_2	Constant in equation (5.24).
B_3	Constant in equation (5.25).
b	The groove breadth in the flow direction.
C	Constant in equation (5.7).
C_1	Constant in equation (2.4).
C_{D_1}	Drag coefficient based on the free stream dynamic head.
C_{D_H}	Drag coefficient based on the dynamic head at the building (or roughness element) height, H.

Symbol

C_{D_m}	Drag coefficient based on the maximum pressure difference across the element.
C_{D_*}	Drag coefficient based on the friction velocity, u_*.
C_f'	Local skin friction coefficient.
C_{f_e}'	Effective local skin friction coefficient, C_{D_1}/A.
C_i	Infiltration coefficient of the opening
C_{p_f}	Pressure correction factor in equation (3.1).
C_{p_l}	Leeward wall mean pressure coefficient.
C_{p_w}	Windward wall mean pressure coefficient.
$\underline{C}_{p_1}$	Pressure coefficient based on U_1.
ΔC_p	Mean pressure difference coefficient across two opposite faces of the model or a building, (based on U_1).
ΔC_{p_H}	Mean pressure difference coefficient across two opposite faces of the model or a building, (based on u_H).
D	Drag force on a building or roughness element.
d	Ground level displacement, zero pla. : displacement.
$\bar{d}$	Mean value of d.
$\underline{E}$	Constant in equation (5.8).

Symbol

E	Mean bridge voltage of the anemometer.
E_d	The reattachment distance downstream the building or any roughness element.
E_o	Mean bridge voltage of the anemometer at zero velocity.
E_t	The sum of the separation and reattachment distances E_u and E_d around the building or any roughness element.
E_u	The separation distance upstream the building or any roughness element.
E_v	Dimension of the stable vortex in the flow direction.
F	Constant in equation (5.18).
F_1	Functional dependence of the inner layer.
F_2	Functional dependence of the outer layer.
F_3	Functional dependence of the windward pressure profile.
F_4	Functional dependence of the leeward pressure profile.
f	Coriolis parameter.
H	Building height, roughness element height.
$\bar{H}$	Average value of H.
H_o	Height of obstructing building.
h	Low building height.

Symbol	
K	Constant in equation (3.2)
K_o	Correction factor to allow for variation of pressure with orientation of building.
k_s	The equivalent sand grain roughness size.
L	Building or roughness element dimension across flow direction.
L_c	Length of the opening (crack).
L_x	Distance of separation between buildings also site length, in the wind direction.
M_3	The simple model used in the first stage of the investigation.
M_{24}	The detailed model used in the second stage of the investigation.
m	Constant in equation (6.1).
m_1	Constant in equation (5.23).
m_3	Constant in equation (5.25).
n	Exponent.
p	Wind pressure on the building surface.
p_1	Leeward wall pressure.
p_{max}	Maximum wind pressure on the building, (or roughness element).
p_{min}	Minimum wind pressure on the building, roughness element).

Symbol

$\frac{\Delta u}{u_*}$	Roughness function.
V	Volume flow rate.
v	Velocity component in the vertical direction.
W	Building (or roughness element) dimension along flow direction.
x	Distance along wind direction, also representing building group fetch.
y	Height above the ground.
y_G	Gradient height at the top of the boundary layer.
z_o	Roughness length.
$\overline{z}_o$	Mean value of z_o.
α	Exponent in the power law.
α_I, α_{II}	Orientation angles of the hot wires (I and II) with respect to the x axis.
γ	Angle of obstruction between buildings.
δ	Boundary layer thickness.
δ_i	Internal layer thickness.
δ_l	Laminar sublayer thickness.
δ_r	Rough flow boundary layer thickness.
δ_s	Smooth flow boundary layer thickness.

Symbol

p_o	The static pressure at the reference point.
p_y	Wind pressure on the building at any height, y.
Δp	Pressure difference across the building.
Δp_o	Pressure difference across any opening.
q_1	The free stream dynamic head.
R	Group layout radius, also the central model fetch.
S	The cube spacing in the flow direction.
$\overline{S}$	The mean spacing of the cubes in the flow direction.
S_c	The clear spacing between the cubes or buildings in the flow direction.
T	Slope of the hot-wire calibration lines.
u	Mean velocity in the wind direction.
u_1	Mean velocity in the free stream.
u_{10}	Mean velocity at 10m above the ground.
u_*	Friction velocity.
u_{eff}	Effective velocity acting on the hot-wire.
u_G	Gradient velocity.
u_H	Mean velocity at height H.
u_y	Mean velocity at any height y.

Symbol

ε	Error in origin for measuring y, ($H = \varepsilon + d$).
θ	The building or central model orientation angle with respect to wind direction.
κ	Universal constant ($\simeq$ 0.4).
λ	Density of building (or roughness element) groups.
λ_f	Frontal area density.
λ_p	Plan area density
ν	Kinematic viscosity of air.
ρ	Density of air.
τ_o	Surface shear stress
τ_{oe}	Effective surface shear stress.
ϕ	The surrounding group angle of orientation with respect to wind direction.
Ψ	Effective angle between the flow direction and the plane normal to the wire axis.
ψ_x	Ratio between building width, W and the site length, L_x.
ψ_y	Ratio between building length, L and the site lateral dimension, L_y.
I, II	Subscript denoting hot wire no.
Δ	Subscript denoting values corresponding to small change in the hot wire effective angle, Ψ.

1. INTRODUCTION

1.1 Natural Ventilation of buildings

1.1.1 Ventilation in terms of supplying fresh outside air into building interiors is one of several means by which the indoor climate of a building could be controlled. Introducing outside air internally may be achieved by means of natural ventilation, mechanical ventilation or air-conditioning. The choice of either method not only has its consequence on the architectural design principles, but also on the building cost and the resulting indoor environment; for example, the building depth and in turn its form is directly affected by this choice. Mechanical ventilation will involve additional initial expenditure and increased running costs which might in some buildings be necessary and may be compensated for economically. The artificial control of ventilation will enable the provision of conditions very close to the required internal environment, in contrast with the natural methods of ventilation which rely on highly variable external climatic conditions. However, in most cases, where the external climatic impacts are not too severe to produce balanced conditions by natural means and when minimum building cost is of prime importance, natural ventilation becomes the only available alternative for the designer. It may also be noted that housing consumption of energy for heating purposes in many countries represents a large proportion of the national energy budget, a considerable part of which is wasted by uncontrolled excessive ventilation.

Therefore a proper estimate of the natural ventilation rates in buildings is necessary if buildings are to meet their environmental and economic requirements.

1.1.2 Natural ventilation occurs in virtually all buildings through the openings in their envelope. Intentional air flow through openings provided in the building, such as windows or ducts is usually referred to as ventilation. On the other hand, unintentional flow may occur through gaps and cracks in the building such as those round windows or doors. This type of flow is known as infiltration. Where ventilation may be allowed or prevented through controlling the ventilation openings, infiltration is usually out of control and subject to variability of the natural forces created in the ambient climatic conditions. However,infiltration rates may be put to minimum if the gaps and cracks round ventilation openings and doors are minimized.

1.1.3 The main principle that operates to produce natural ventilation in buildings is the existence of a pressure difference between the inside and the outside of the building. The magnitude of the pressure difference and the flow resistance will determine the rate of air flow through the openings. The size, shape and location of openings determine the speed and pattern of internal flow. The two forces that produce pressure differences across building elements are the wind force and the thermal force, known as "stack effect". Due to air flow around a building, different pressures are exerted on its external surfaces. For an isolated building of simple rectangular form with a flat roof, if the wind is normal to one of its sides, positive pressures develop on the windward wall and negative pressures on the roof and the rest of the walls. The pattern of the pressure distribution as well as its magnitude will depend mainly on the properties of the oncoming flow, the building form and other parameters relating the building to the flow. This point is discussed in detail in Chapter 2.

1.1.4 Ventilation may also occur, though to a lesser extent, either due to pressure fluctuations on the walls, an action related to the turbulent nature of the wind, or due to turbulence diffusion. Although the magnitude of ventilation provided by these two mechanisms is normally negligible, it could be of considerable weight in situations where only one opening is provided to the space or during the absence of both wind and thermal forces.

1.1.5 Natural ventilation principles have been established through the extensive studies made either on full scale buildings or on scale models. However, a detailed accurate description of the natural ventilation occurring in any building of moderate complexity appears to be very diffucult, Bilsborrow (1973). This is partly due to the lack of an accurate practical measure of the effectiveness of ventilation, but probably mainly due to the complex interaction of the factors affecting the ventilation potential in any circumstances. At present the accepted measure is the rate of air flow, m^3/hr, sometimes expressed in terms of the number of a certain volume (usually taken as the room volume or the total building volume) per unit time, air change/hr.

1.2 Natural ventilation calculation

1.2.1 The two common methods currently in use for natural ventilation calculations are the air change method and the crack method. Both methods are described in the IHVE Guide (1970) and the ASHRAE Guide (1972). The air change method which is entirely emperical is based on the assumption that similar building types of typical construction and normal use in winter would have similar infiltration rates. Therefore, tabulated values of infiltration rates are given for different building types assuming normal exposure and an average ratio (25%) of openable areas (windows and doors) to external wall area. Allowance of 25-50% is given for higher ratios of openable areas in the external walls as well as for different degrees of building exposure. The latter being 50% increase for severely exposed sites and 33% decrease for sheltered sites. The three degrees of building exposure are classified as follows:

Sheltered:	Up to third floor of buildings in city centres.
Normal:	Most suburban and country premises: fourth to eighth floors of buildings in city centres.
Severely Exposed:	Buildings on the coast or exposed on hill sites: floors above the fifth of buildings in suburban or country districts: floors above the ninth of buildings in city centres.

In the air change method quoted in the ASHRAE Guide, allowance is made for opening distribution in the external wall and weather stripping. A reduction of 33% is made in the latter case.

1.2.2 The crack method for infiltration calculation is based in principle on the following equation which relates the ventilation rate, V, to the pressure difference, Δp_o, acting across any opening,

$$V = C_i . L_c \; (\Delta p_o)^{1/n} \qquad \ldots\ldots \qquad (1.1)$$

For a particular building, the infiltration coefficient, C_i, and the crack length, L_c, are dependent on the type and the area of the openings respectively. From the work on air flow through openings, a relationship is shown to exist between C_i and the exponent n, Bilsborrow (1973). Therefore, it remains to determine Δp_o in equation (1.1) in order to obtain the ventilation rate, V. From the work on air flow round building models an estimate of the mean pressure difference across the building Δp, may be obtained, half of which is assumed to act across each of the windward and the leeward faces of the building, giving Δp_o. The main assumption made in the IHVE Guide to estimate the mean pressure difference across any building, Δp, (hence Δp_o) is that the velocity pressure of the wind at the roof top level is approximately equal to Δp. Therefore, for one design wind speed and three velocity profiles assumed to occur on three different sites (open country, suburban areas and city centres) the corresponding velocity pressure profiles are plotted. These velocity pressure profiles are then used to obtain Δp for buildings of any given height in the three site conditions. It seems that the main assumption made in the IHVE Guide to estimate Δp may result in considerable error since important factors affecting Δp such as the building form and the properties of the oncoming flow are neglected. The effect of these factors is well documented (see for example the Code of Practice CP3, Chapter V, part 2 (1972) and the work of Jensen and Franck (1965)). The conclusions that can be made from the above discussion is that the accuracy level of the ventilation rate using the crack method depends on the accuracy of determining the pressure difference across the building, Δp, in different sites. Therefore it is important to consider the factors affecting Δp if any reliable estimate of the ventilation rate is to be made.

1.3 The factors affecting the pressure difference across buildings

1.3.1 There are a large number of variables affecting the pressure difference across buildings in the natural wind. The complexity of interaction between these variables and the difficulty of controlling them in nature called for the dependence on the scale model experimental work as a main source of information. In particular the work done on the drag (hence Δp) of bluff bodies immersed in turbulent boundary layers provide the basic information required, see for example the work of Good and Jourbet (1968), Jensen and Franck (1965), Morris (1955), Joubert, Perry and Stevens (1971) and Wooding, Bradley and Marshall (1973).

From this work the similarity of wind flow over the earth's surfaces to the turbulent boundary layer flow over rough surfaces is established. Hence, buildings on the earth's surface may be considered as elements on a rough surface over which a turbulent boundary layer flows.

1.3.2 By definition, the drag exerted on any bluff body in boundary layer flow is the difference between the integral of the windward and the leeward pressures. These pressures are determined by the process of separation and reattachment of air flow round the body. Although the factors affecting separation are not necessarily the same as those affecting reattachment, it seems logical to classify all the factors involved into the following two groups:

(a) factors related to the building form, and

(b) factors related to the properties of the wind.

The main properties of form known to affect the drag of buildings in urban areas are:

(a) individual form, and

(b) group form.

Individual building form is the only form factor affecting the drag of isolated buildings and may be broken down to:

(i) building shape, (ii) building size and

(iii) building permeability.

1.3.3 The effect of varying rectangular building shape on the drag coefficient, C_{D_H}, is well documented in the Code of Practice CP3 (1972). The method of determining the wind pressures on buildings, used in CP3, utilizes a design wind speed and a drag coefficient C_{D_H}. For a particular case, the height of the building is taken into account since the reference dynamic head is that appropriate to the top of the building. The value of C_{D_H} used simply takes account of the building geometry. However, the extensive work of Good and Joubert (1968) and Jensen and Franck (1965) has deomonstrated that for buildings in the turbulent boundary layer, the size of the building alone in a particular flow situation will influence C_{D_H}. The third prcperty of individual form that affect the drag coefficient, is the building permeability, though relatively less information is available in the literature to illustrate its effect. The full scale measurement on Royex House reported by Newberry, Eaton and Mayne (1973) indicate that permeability reduced the pressure difference across the building by a factor of about 30%.

1.3.4 In the case of low building density where buildings are wide apart i.e. in open country, the individual building form is the only form that the wind can "see". As the density increases, i.e. in suburban and urban areas, buildings are close to each other so that each building form becomes a detail in the group form as a whole. In this case the group form becomes more important than the individual building form in influencing the drag forces experienced by each building. Recent experimental work (see for example Joubert, Perry and Stevenson (1971)) shows how the group geometry of roughness elements simulating buildings immersed in turbulent boundary layer flow affect the drag force on each element.

1.4 Formulation of the problem and the pattern of investigation

1.4.1 In the discussion so far, the problem of estimating a reliable value of Δp for natural ventilation calculation is shown to depend on two main groups of factors, i.e. form-related factors and flow-related factors. Thus, in urban areas where buildings are mostly in groups, it is expected that the two main factors affecting Δp are (i) the group form and (ii) the properties of the natural wind. Therefore, in an attempt to gain further understanding of the wind flow and more important the pressure forces in urban areas, it is intended to carry out a detailed investigation on the interaction between group geometry, properties of air flow and the resulting pressures. It is hoped that a relationship may be obtained between the group geometry, and the resulting pressure forces and also between the group geometry and the interacting flow. If this is the case, then a relationship must exist between the pressure forces and the flow properties. Such relationships may well exist since similar relationships between the flow properties, the element form and the resulting pressures are reported by Good and Joubert (1968) for the simple case of a two dimensional isolated element in smooth surface flow.

1.4.2 In order to cover the different aspects of form and flow in urban areas in the present investigation, and because of its implications on planning decisions, it was necessary for the investigation to meet the theoretical aspects as well as the practical aspects of different fields.

For example the investigation of air flow is to meet both the practical aspects of air flow in the natural wind as well as the theoretical aspects of turbulent boundary layer flow over idealized rough surfaces. The geometry of building groups must also consider the practical aspects of the planning parameters as well as the theoretical aspects of form description. Consequently, the following pattern of investigation emerged, to meet these diverse requirements.

1.4.3 Since the properties of flow in the natural wind are important factors in determining the pressure forces on buildings, they are first considered in Chapter 2. A review on the previous work on the wind pressure and flow over groups of buildings is made in Chapter 3 so that relevant information may be obtained. In Chapter 4 the different aspects of density and form are investigated in an attempt to link the planning parameters in urban areas to the geometrical parameters describing various arrays of rectilinear elements simulating building groups. Since buildings may be considered as roughness elements on the earth's surface over which the atmospheric boundary layer flows, the idealized case of flow over rough surfaces is discussed in Chapter 5. From this Chapter an understanding of the interaction between the flow, the roughness geometry and the resulting pressures is achieved. At the end of Chapter 5 it is shown that further investigation is needed to close the gap between the idealized theoretical case and the practical case of buildings in the natural wind.

1.4.4 In Chapters 6 - 8 the results of the experimental investigation carried out in the present work using cubes as a simplified building form are explained and discussed. The main variables considered are:

(a) the properties of the oncoming flow: two different flow conditions,

(b) the group form: including a wide range of group density and pattern and

(c) the resulting pressure forces: detailed pressure measurements on two opposite faces of the cube.

Pressure measurements were made from a pressure tapped model within the group. Velocity profile measurements were also made for the flow over the different groups considered. The measurement techniques, the accuracy level and the set up of the models and equipment is given in Chapter 6. Following in Chapter 7, the discussion on the pressure measurement results is given and a hypothesis concerning the flow behaviour is made. The flow measurement results given in Chapter 8 enabled a check to be made on the hypothesis outlined in Chapter 7 as well as providing information about relevant velocity profile parameters. This information enabled a comparison to be made between the results obtained and the established work on flow over roughness. In addition it enabled correlations to be made between the different parameters considered. The flow visualization experiments are presented in Chapter 9 and a discussion is given on the way in which these results can be used to substantiate the hypothesis for the existence of different flow regimes formulated in Chapters 7 and 8.

1.4.5 In Chapter 10 a more general discussion is presented on the application of this study to the building designers problems. The guide lines of an alternative method for the prediction of the pressure differences across buildings is given in an attempt to improve the current IHVE Guide method for the calculation of infiltration rates. Finally in Chapter 11 the general conclusions reached in the thesis are summarized.

CHAPTER 2

THE PROPERTIES OF THE WIND AND THEIR INFLUENCE ON THE PRESSURES ON BLUFF BODIES.

2. THE PROPERTIES OF THE WIND AND THEIR INFLUENCE ON THE PRESSURES ON BLUFF BODIES

2.1 The structure and behaviour of the natural wind

2.1.1 The main flow variables in the natural wind that affect the drag of buildings are the velocity profile of the wind, wind turbulence and wind direction. Before discussing their effect on the drag of buildings some background information about the structure and behaviour of the natural wind is given.

2.1.2 The structure of the atmospheric boundary layer is highly complicated. This may explain the fact that although many experiments are being and have been made of the atmospheric boundary layer, much more information is needed concerning its detailed flow structure and flow patterns, Counihan (1975). In the atmospheric boundary layer, wind properties are dependent on both the upper boundary conditions which are the Gradient wind speed and its direction, and more important the lower boundary conditions the topography, surface roughness and surface temperature at the earth's surface. This boundary layer may be regarded as the layer from which momentum is directly extracted and transferred downward to overcome the aerodynamic friction arising from the motion of the air relative to the earth's surface, Pasquill (1970). Within the boundary layer, regions of different properties can be identified. Close to the surface, the shear stress is approximately constant and independent of height. Wind direction is also independent of height. This defines the "roughness layer" or "surface layer" which extends from the ground up to about 30 metres in open country and 100m in urban areas, after which this approximation breaks down, Counihan (1975). On top of the roughness layer and occupying the rest of the boundary layer is"Ekman layer". In this layer the shear stress decreases with height from its maximum value at the roughness layer to zero at the Gradient wind, a height of some 300-600 meters. Another characteristic of this layer is that wind direction also changes with height in a clockwise rotation known as "Ekman spiral". Within large surface roughness, such as in urban areas, we may define an "interfacial layer" in which the downward flux of momentum is transferred to pressure forces acting on the surface roughness elements themselves, Pasquill (1970). This layer is characterized by wake flows and large variations of static pressure.

2.1.3 Over land, the earth's boundary layer is always adapting to changes of surface roughness. It is observed that an internal layer grows from the surface at a roughness change and develops until it displaces the old layer, Elliott (1958), Munn (1966). In nature the normal fetches of towns are not sufficient for the boundary layer to adapt fully, (i.e. the velocity profile does not change with fetch), before the surface roughness changes again. However, in the lower layers close to the surface, adaptation to roughness change takes place very rapidly and relatively short fetches (≈ 100-500 meters) may be required for these layers to adapt completely, BRE Digest 119 (1970).

2.1.4 The structure of atmospheric turbulence is usually described by the existence of eddies of different sizes and highly irregular shape in the atmospheric boundary layer. In general the eddy size increases with distance above the ground as there will be more room for larger eddies to grow. It is postulated that eddies comparable with the boundary layer height exist in the earth's boundary layer, Townsend (1951). As a result of this eddy cascade, the wind speed changes continuously with time, and the mean value of the wind speed is then dependent on the period taken for averaging. The energy contained in the eddies can be analysed for different frequencies to yield a spectrum similar to that shown in Figure 2.1, Van der Hoven (1957). From the discussion on this spectrum made by Davenport (1963) the following may be quoted:

"One of the most important distinctions that it appears can be made is between the fluctuations of a macrometeorological kind such as the movement of large-scale pressure systems, seasonal variations etc. and those which are of a local, micrometeorological kind and associated with the flow characteristics of the boundary layer itself" ..... "It appears that these two types of fluctuations are separated by a gap extending from roughly five minutes to five hours. This gap is important to our evaluation of wind loads for several reasons. It enables a clear cut distinction to be made between gusts and weather-map disturbances and furthermore their causes: in another sense this distinction can be

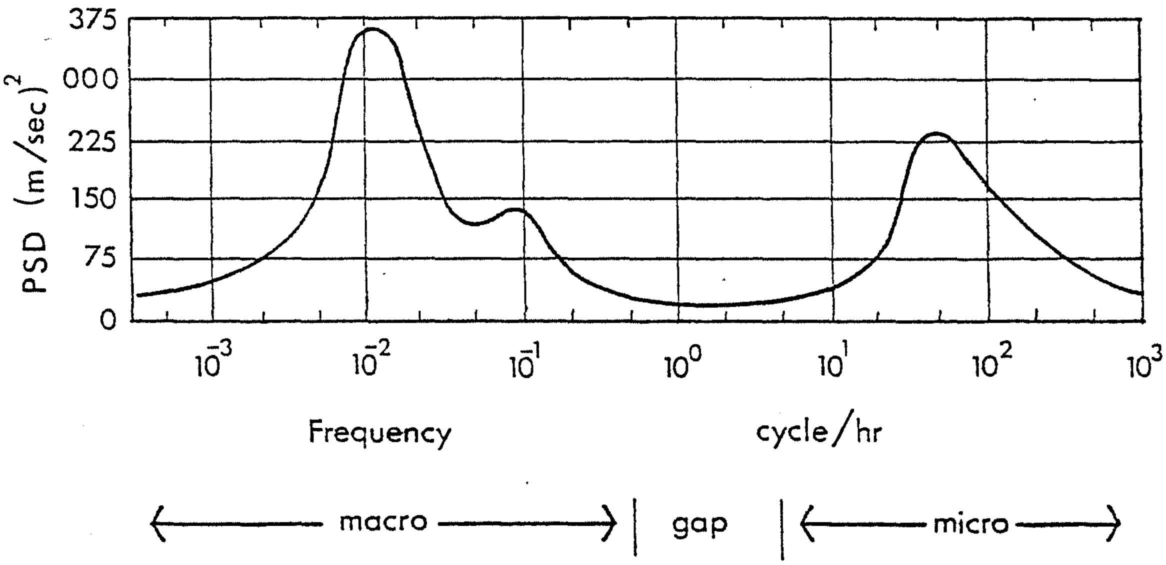


Figure 2.1 SPECTRUM OF THE HORIZONTAL WIND COMPONENT, (after Van der Hoven, 1957).

regarded as between gusts and the mean wind where the mean wind is characterized by the average velocity over some period within the spectral gap".

2.1.5 In the discussion so far, the wind direction has been considered constant.

As this is not the case in natural wind where these variables are constantly changing, wind may blow from different directions throughout the year for various periods of time. The statistical analysis and presentation of wind speed in terms of percentage of time and direction is known as a wind rose (see Figure 2.2) and is necessary for each site due to climatic variations and the local effect of topography or large obstruction on the prevailing wind direction. A change in wind direction for a building on a site may result in completely different flow conditions due to the corresponding change in the surface roughness up wind.

2.1.6 It is well known that in boundary layer flow over flat surfaces the flow speed changes with the distance from the surface. For the earth's boundary layer, several emperical forms have been suggested to describe the velocity profile of the wind. The two "laws" in common use are the "power law" and the"log. law". The power law takes the simple form of:

$$\frac{u}{u_G} = \left(\frac{Y}{Y_G}\right)^{\alpha} \qquad \ldots \quad \ldots \qquad (2.1)$$

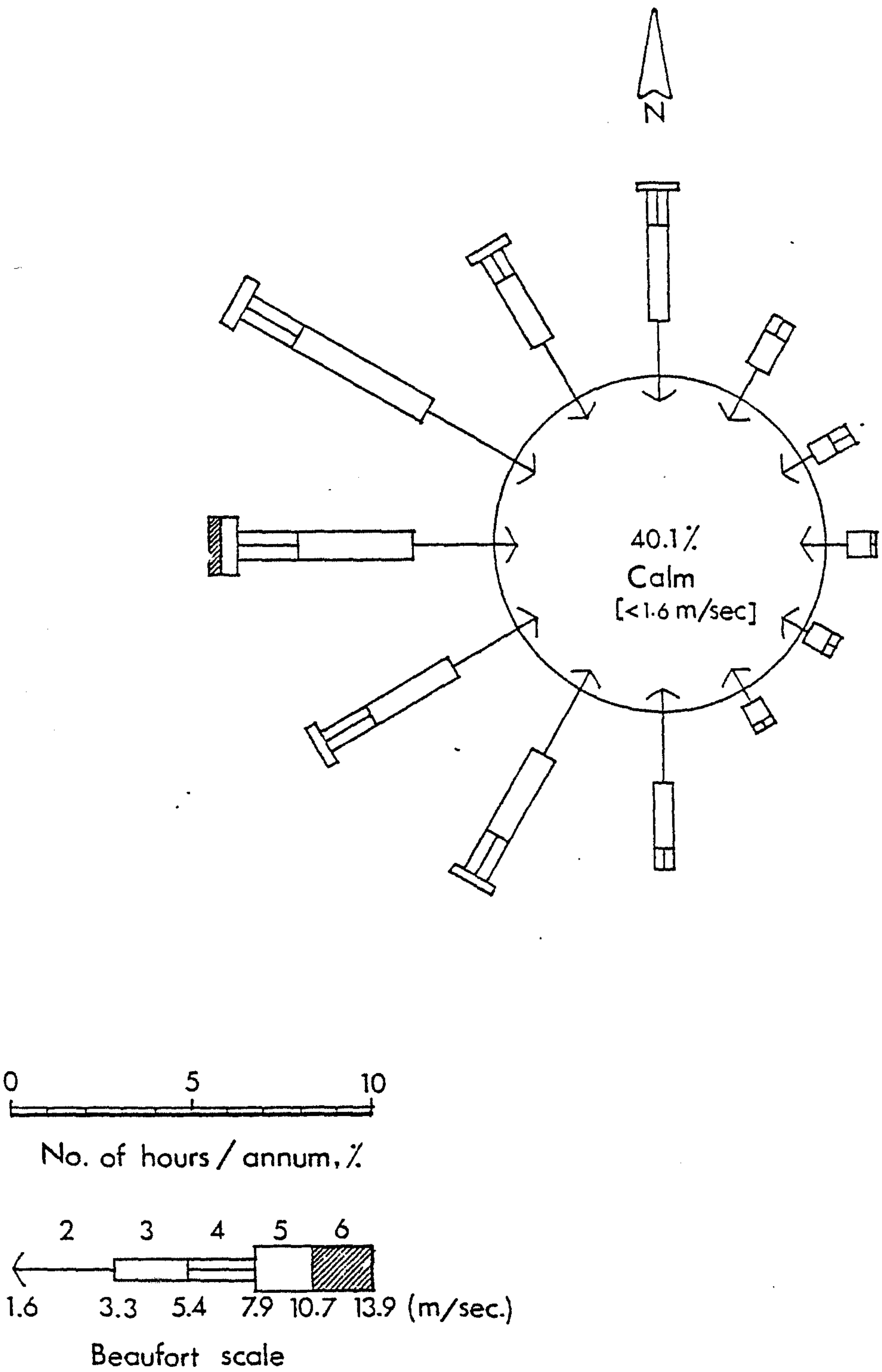


Figure 2.2 WIND ROSE DIAGRAM FOR SHEFFIELD, (replotted from Lee, B., 1975,C)

where u_G is the Gradient wind speed and y_G is the Gradient height (the boundary layer height). Davenport (1963) collected together mean wind speed profile data for a wide range of countries and terrains. He showed that the index of the power law, α, and the Gradient height, y_{G*}, varied with the nature of the terrain and suggested the representative values shown in table 2.1 and Figure 2.3.

Table 2.1 Variation of the exponent α with type of terrain

(After Harris,1972)

Type of terrain	Exponent α	Gradient height y_G (m)
Grassland	0.16	280
Woodlands, Suburbia	0.28	400
Urban Centres	0.40	430

The extensive amount of available data for lakes and mud flats through to suburban terrain confirms that the exponent α could take the value of 0.11 up to 0.3 respectively. However, the values for urban terrain are less well established, Harris (1972), Caton (1975).

2.1.7 As an alternative approach, the application of boundary layer theories based on experiment to the earth's natural boundary layer was preferred by metereologists due to the emperical nature of the "power law". In strong winds and neutral stability the wind flow on the earth's surface is completely turbulent. Therefore a logarithmic law of the form:

$$\frac{u}{u_*} = \frac{1}{\kappa} \ln \frac{y}{Z_o} \qquad \ldots\ldots \qquad (2.2)$$

where $y \geq Z_o$, was proposed, Sutton (1953)

This equation is meaningless for $y < Z_o$. To satisfy the condition $u = 0$ on $y = o$, the above equation may be written as,

$$\frac{u}{u_*} = \frac{1}{\kappa} \ln \frac{y+Z_o}{Z_o} \qquad \ldots\ldots \qquad (2.3)$$

This equation is approximately the same as equation (2.2) for small values of Z_o and large values of y. Typical values of the roughness length, Z_o, for different types of terrain are given in table 2.2.

Table 2.2 Values of Z_o for various types of terrain

Type of terrain	Z_o(m)	Reference
Very smooth (mud flats, ice)	0.00001	Sutton (1953)
Lawn, grass up to 0.01m	0.001	Sutton (1953)
Downland, thin grass, up to 0.1m	0.007	Sutton (1953)
Thick grass, up to 0.1m	0.023	Sutton (1953)
Thin grass, up to 0.5m	0.050	Sutton (1953)
Thick grass, up to 0.5m	0.09	Sutton (1953)
Rural terrain	0.10	Counihan (1972)
Suburban terrain	1.0	Counihan (1972)
Urban terrain	2.50	Counihan (1972)

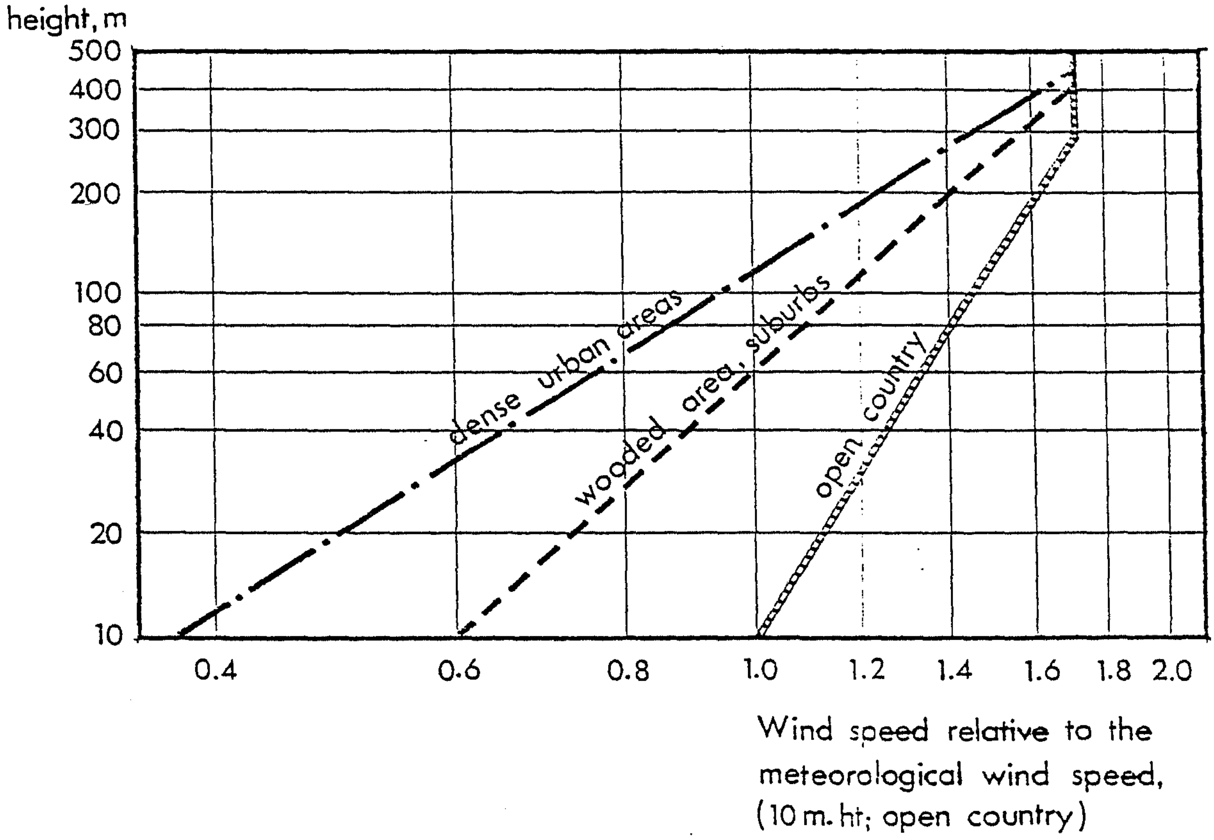


Figure 2.3 MEAN WIND VELOCITY PROFILES FOR SURFACES OF DIFFERENT ROUGHNESS, (after Davenport, 1965).

It may be noted that the form of the logarithmic law as in equation (2.2) applies only to the constant shear stress layer, i.e. the roughness layer. To extend the validity of the logarithmic law to Ekman layer where the shear stress is no longer constant, a linear term should be added and equation (2.3) takes the form, Harris (1972).

$$\frac{u}{u_*} = \frac{1}{\kappa} \ln \frac{y + Z_o}{Z_o} + C_1 f y \qquad \ldots\ldots \qquad (2.4)$$

where f is the Coriolis parameter,and C_1 is a function of u_*, Z_o, f and the Gradient velocity and wind deviation between ground level and Gradient height.

2.1.8 In the case of flow over urban areas, the flow assumes a ground level displacement, d, therefore equations (2.2) and (2.3) should be modified to read:

$$\frac{u}{u_*} = \frac{1}{\kappa} \ln \frac{y - d}{Z_o} \qquad \ldots\ldots \qquad (2.5)$$

and

$$\frac{u}{u_*} = \frac{1}{\kappa} \ln \frac{y - d + Z_o}{Z_o} \qquad \ldots\ldots \qquad (2.6)$$

The model for flow in urban areas proposed by Harris (1972) shown in Figure 2.4 and based on equation (2.6) assumes three zones of flow, "A", "B" and "C". Region "A" represents that part of the flow described by a logarithmic profile similar to equation (2.6). While in region"C", i.e. within the displacement height, apart from the fact that wind speed is zero at zero height no general law is applicable and the flow is determined by the adjacent buildings. Finally region"B" is simply a transition from region "A" to region "C". More important is the assumption that,

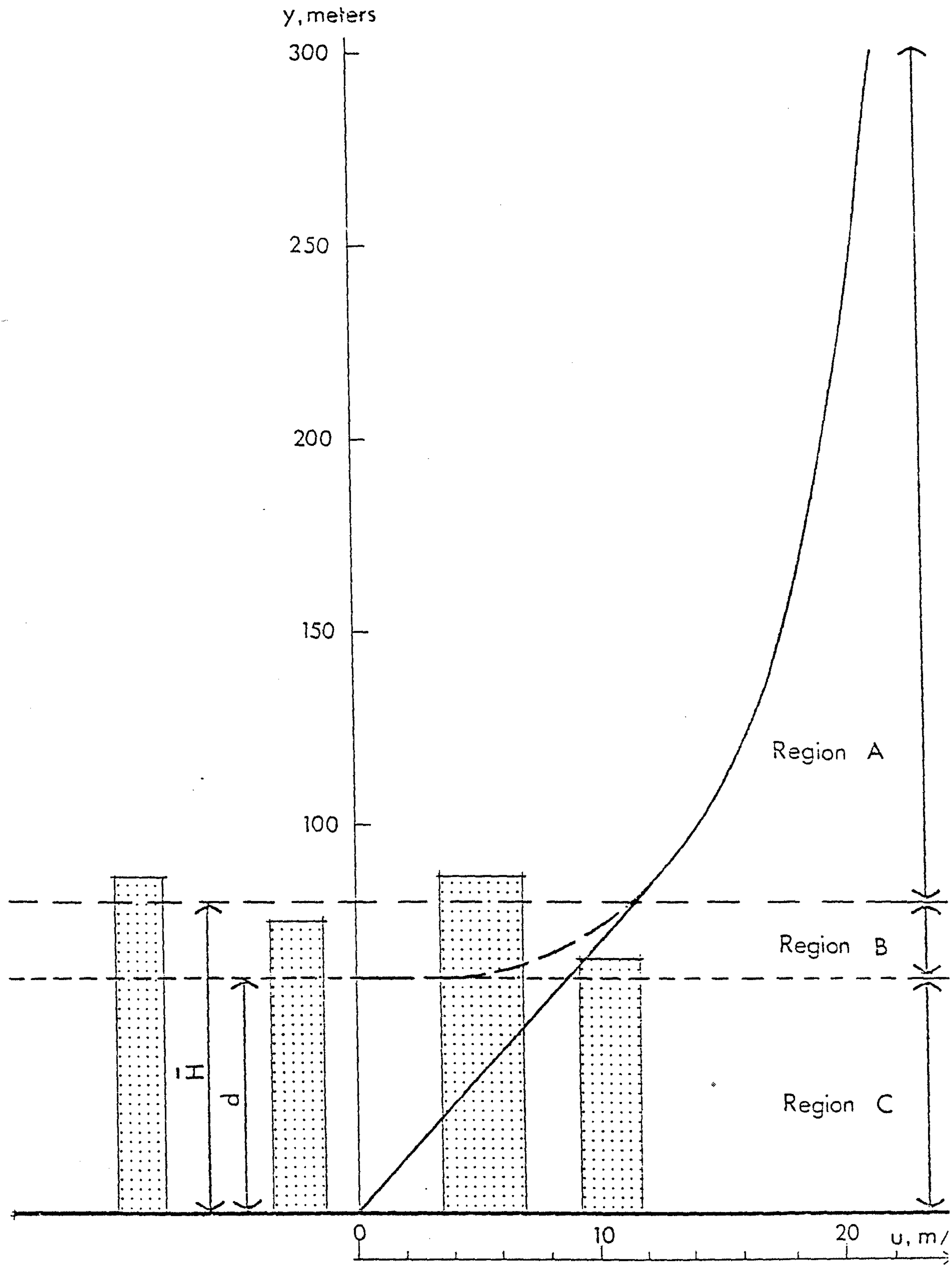


Figure 2.4 A MODEL FOR AIR FLOW IN URBAN AREAS, (after Harris, 1972).

d, is of the same order of the average building height $\overline{H}$ and no profile law can be expected to fit data above an urban terrain below a height of about 1.5d. In the present study these assumptions are examined.

2.2 Effect of flow parameters on the mean pressure difference across buildings

2.2.1 From wind tunnel experiments, the effect of wind direction, turbulence and the velocity profile parameters on the mean pressure difference across buildings is established. However, the comparison between full scale and model results provide some basic information, see for example Jensen and Franck (1965). The effect of varying wind direction on the pressure difference, Δp, has two-fold effect. First, variation of wind direction might imply completely different flow conditions due to variation of upstream surface roughness, hence different turbulence characteristics and velocity profiles. Second, varying wind direction might change Δp across two opposite faces of a building. Dick (1949) noted in his full scale studies on natural ventilation of houses, that wind direction is of negligible effect. However, this might not be the case for:

(i) buildings of long plan shapes

(ii) buildings grouped at large spacings and

(iii) where ventilation openings are only supplied on two opposite faces of the building.

Under these conditions, the driving force for ventilation is the mean pressure difference, Δp, across the faces, rather than the drag force, D, in the flow direction. The drag force may show little variation due to the change in wind direction, hence ventilation is expected to reflect the same trend of, D, for buildings not satisfying conditions (i) and (iii). On the other hand if conditions (i), (ii) and (iii) are satisfied, the mean pressure difference across two opposite faces may range from a maximum equal to the drag force, at normal incidence to a minimum for the wind at right angles. Therefore, information about wind directions in nature is necessary if any estimate of Δp is required.

2.2.2 It is known that turbulent scale and intensity affect the drag coefficient of rectangular body forms through its effect on the separated flow region, Lee (1975 (a)), Lee (1975 (b)). On three dimensional rectangular forms, very little work exists, apart from that by Cook (1972) where only the effects of turbulence scale or intensity were investigated independently. Jensen and Franck (1965) conducted wind tunnel experimental work in which the flow structure was varied using different surface roughness upstream the model, on which the boundary layer naturally developed. Although no attempt was made to measure the associated turbulence characteristics or to reproduce the atmospheric turbulence structure, it was implied that modelling the correct ratio of H/Z_o in natural wind was closely related to modelling the turbulence properties.

In general it appears that higher turbulence intensities reduce the pressure difference by increasing the negative leeward pressure. On the other hand, effects of turbulence scale would appear to be dependent on the ratio of eddy size to building dimensions. Dominant effects would occur at values of this ratio ranging between 0.5 - 10, Cook (1972), Armitt (1974).

2.2.3 The main parameters of the boundary layer velocity profile known to affect the flow mechanism, hence the pressures and the drag force on bluff bodies, are the boundary layer thickness, δ, the roughness length, Z_o, the zero plane (ground plane) displacement, d and the friction velocity u_*. The effect of increasing the ratio $\frac{H}{\delta}$ and $u_1/\ddot{u}_*$ on the drag of a two dimensional plate normal to the flow on a smooth surface was investigated by Good and Joubert (1968). In this study, Good et. al. showed how C_{D_1} as well as C_{D_H} are dependent on H/δ and $\frac{H}{\nu/u_*}$, hence H/Z_o, since ν/u_* is a length scale proportional to Z_o for smooth surface flow. Their results may be seen in Figures 2.5 and 2.6

2.2.4 The work of Jensen and Franck (1965) not only shows the effect of the ratio H/Z_o, for various rough surfaces, on the pressure difference (see Figure 2.7) but also on the pressure distribution as can be seen in Figure 2.8. In this work although no allowance seems to have been made for d in determining the values of Z_o, the effect of variations of Z_o as a parameter of value was demonstrated. Due to the dependence of Z_o or d in the cases where high roughness elements were used, large values

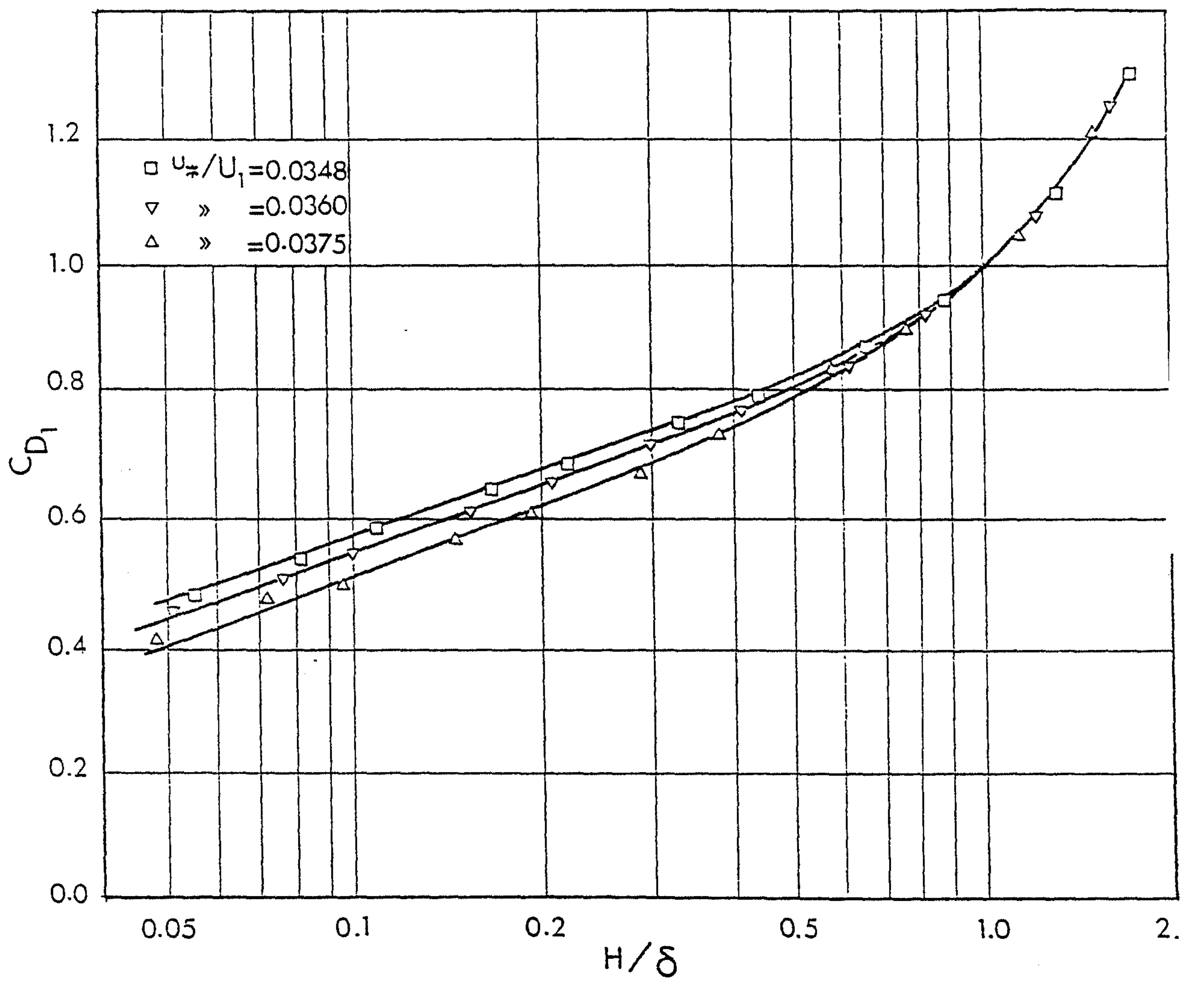


Figure 2.5 VARIATION OF C_{D_1} WITH H/δ and u_*/U_1,
(after Good and Joubert, 1968).

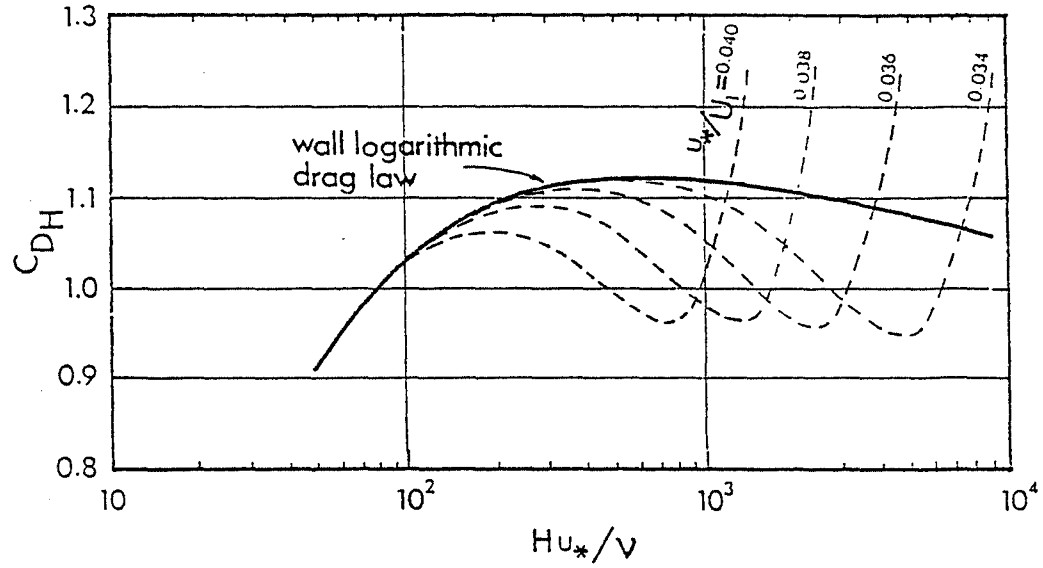


Figure 2.6 VARIATION OF C_{D_H} WITH Hu_*/ν and u_*/U_1, (after Good and Joubert, 1968).

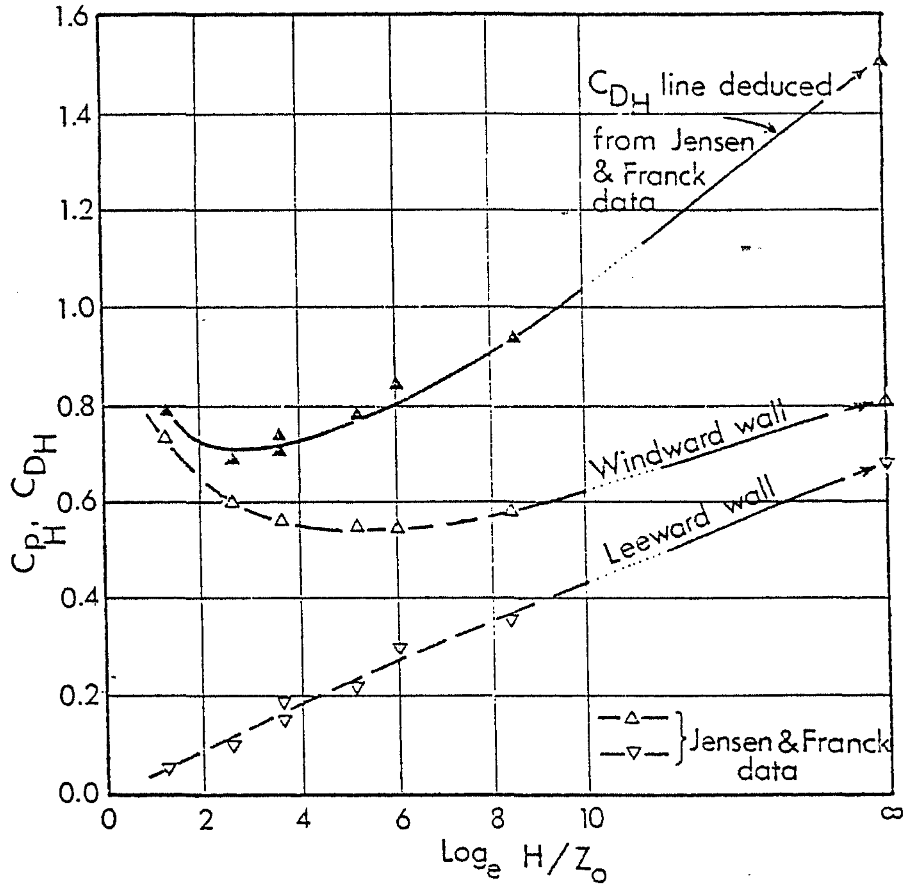


Figure 2.7 VARIATION OF C_{D_H} WITH H/Z_0 AS DEDUCED FROM JENSEN AND FRANCK DATA, (1965).

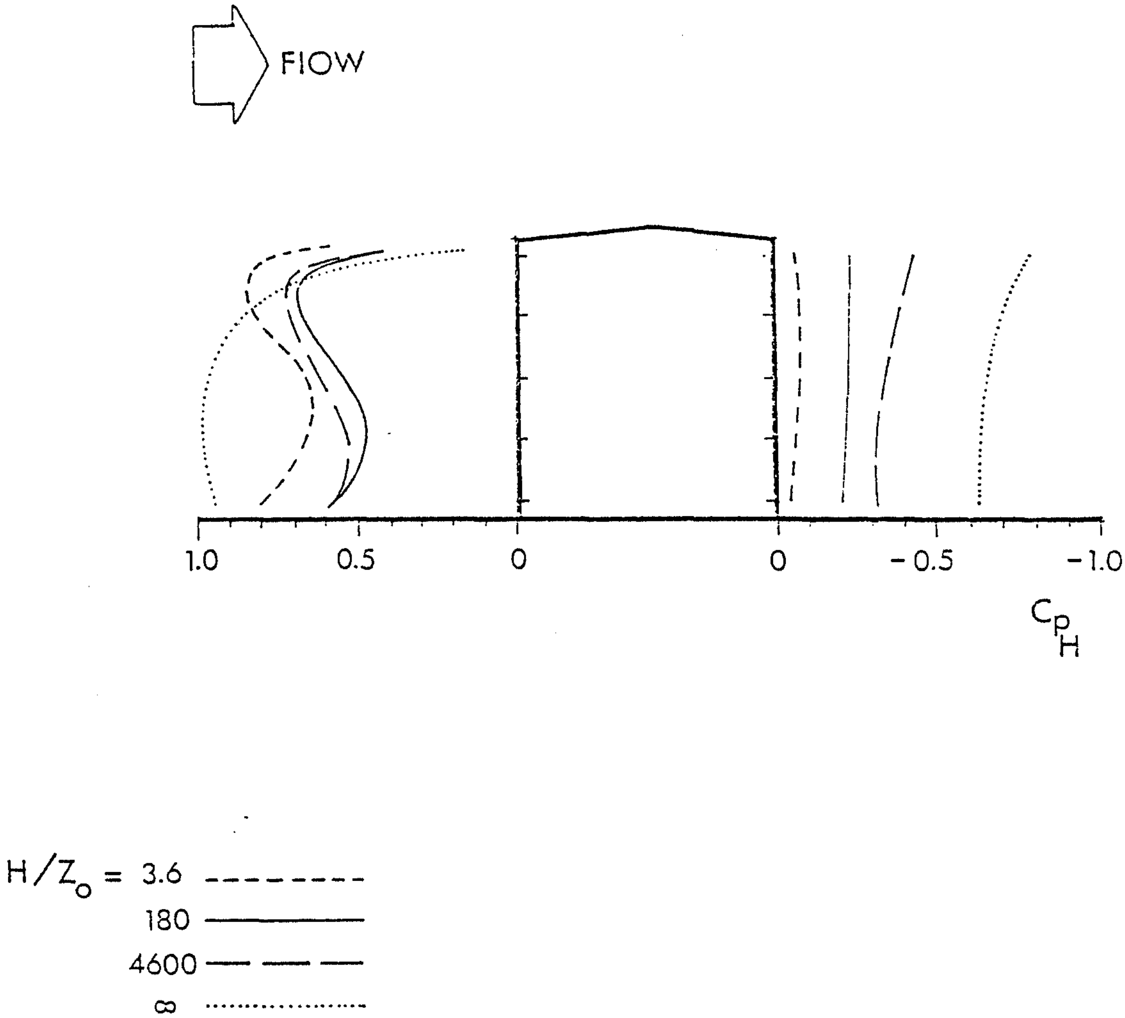


Figure 2.8 THE PRESSURE DISTRIBUTION OF A MODEL HOUSE FOR DIFFERENT VALUES OF H/Z_o, (after Jensen and Franck, 1965).

of d are to be expected. Hence the corresponding values of Z_o are possibly an overestimate.

2.2.5 It may also be noted that due to the disturbance of the flow and the growth of an internal layer (referred to in 2.1.3) at a change of surface roughness, the shear stress at the surface, hence u_*, experience a sudden change followed by gradual change until the value of the new shear stress is attained, Blom and Wartena (1969). Consequently, the drag force on large groups of bluff bodies reflects the same disturbance experienced by u_* at the leading part of the group as well as the trailing part of the group, Antonia and Luxton (1971), Antonia and Luxton (1972). In between these two parts, adaptation takes place. However, for very small groups of bluff bodies, the drag force may not reach stability before the disturbance of the trailing part is experienced. The detailed discussion on the behaviour of the flow parameters is given in Chapter 5.

CHAPTER 3

A REVIEW ON PREVIOUS WORK RELEVANT TO NATURAL VENTILATION OF BUILDING GROUPS.

3. A REVIEW ON PREVIOUS WORK RELEVANT TO NATURAL VENTILATION OF BUILDING GROUPS

3.1 Introduction

3.1.1 Over the years a considerable amount of work has been done in the investigation of wind effects on buildings for various purposes, which might be broadly categorized as wind loading, wind environment and the natural ventilation of buildings. Most of the work has concentrated on isolated buildings, while groups of buildings have received comparatively very little attention. Hence, because of the interrelationship between building form, wind flow and the resulting pressure forces, the findings of any particular investigation will be useful not only for its original purpose but also may help with the solution to other problems in related categories. With the factors affecting the pressure difference across buildings in mind, it is intended in this section to give a review of the previous work on building groups. It will include the relevant work made on:

1. Natural ventialtion of building groups, by Weston (1956), Givoni (1968) and Nelson (1971).
2. Wind loading on building groups, by Vincent and Bailey (1943) and
3. Air flow round groups of buildings, by Wise, Sexton and Lillywhite (1965), Wise (1970), Olgyay and Olgyay (1963) and Koenigsberger, Ingersoll, Mayhew and Szokolay (1973).

3.2 Previous work on natural ventilation of building groups

3.2.1 In the work reported by Weston (1956), the effect of obstructing a simple industrial building by other different building forms placed at different upstream distances was investigated. Measurements of average internal air speeds were made in a 1/16 scale model, for different obstruction cases, the results being presented in the form of the percentage of the mean internal air speed obtained for the same building when unobstructed. For ease of comparison, all dimensions which were given in the report, in full scale equivalent, are given here normalized by the windward wall height, H, of the experimental building (4.57m in full scale). Table 3.1 gives the dimensions of the experimental building together with average and extreme values of the 18 different obstructing buildings used.

Table 3.1 Dimensions of the buildings used by Weston, E.T.

Dimension	Experimental Building	Obstructing Buildings min	Obstructing Buildings avg	Obstructing Buildings max
Building length (across wind)	4H	3.07H	4.04H	6.67H
Building depth (along wind)	12H	1H	2.71H	4H
Building height	1H	0.67H	1.82H	2.73H

From the information given by Weston, the results obtained from the different obstructing buildings were averaged and the standard deviation was calculated. This form of presentation is shown in Figure 3.1 which shows the effect

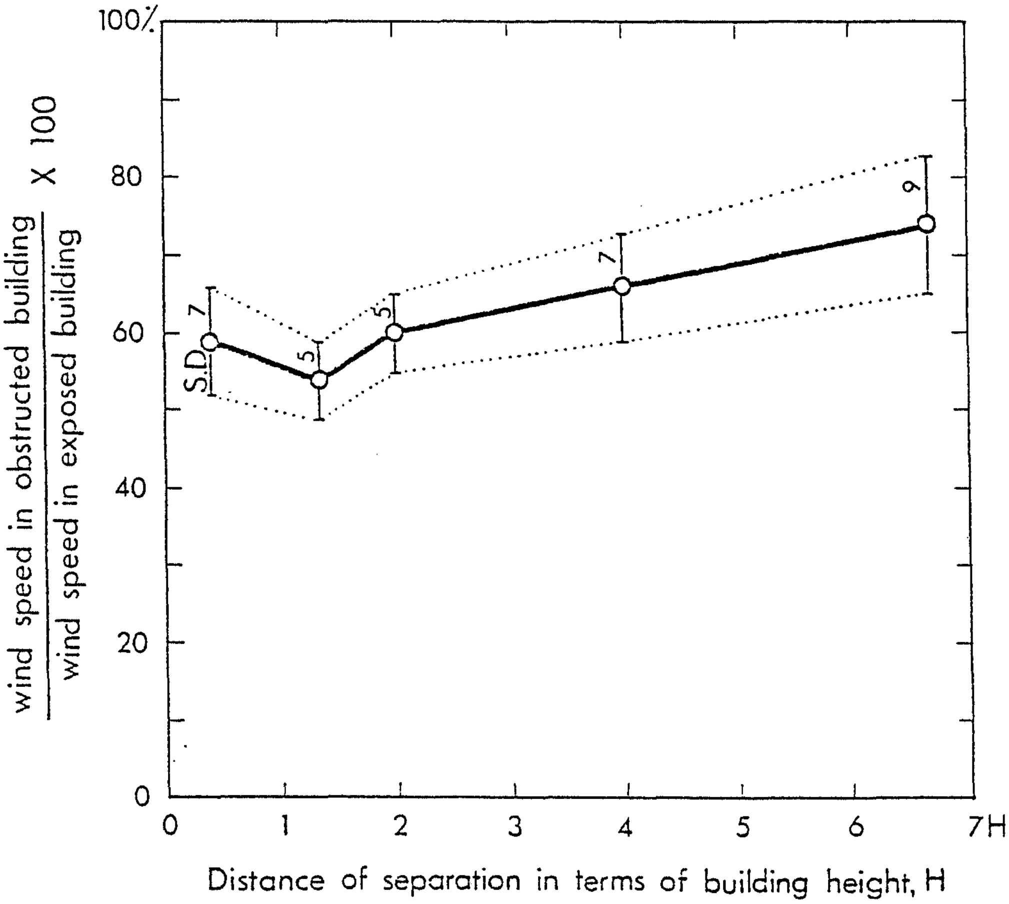


Figure 3.1 EFFECT OF DISTANCE OF SEPARATION ON THE RESULTING VENTILATION USING WESTON'S DATA (1965).

of the distance of separation on the internal air velocity. From this work Weston drew the following conclusions:

(i) As a general rule, increasing the distance of separation between the building and its obstruction improves the natural ventilation.

(ii) There is a certain distance of separation at which a change of flow conditions appears to occur, in that, ventilation conditions are found to be at a minimum and to improve by any increase or decrease in the distance of separation. For most of the cases tested this distance was found to be 1.33H (see Figure 3.1).

(iii) At small distances of separation natural ventilation improved by increasing the height of the obstructing building. The reverse occurred if the distance of separation is increased beyond 2H.

(iv) A similar effect was obtained, though to a lesser extent, by increasing the length of the obstructing building normal to the wind.

The explanations given in the report of these phenomina were assisted by the use of smoke flow visualization techniques and may be summarized as follows. Ventilation conditions improve if the pressure difference across the building increases. At small distances of separation (i.e. less than 1.33H) the windward building wall is in the reduced pressure zone of the obstructing building and becomes subject to a lower pressure than that at the leeward wall

In this case reversed flow was noted in the test building. Decreasing the distance of separation intensified these conditions, hence improving natural ventilation. At larger distances of separation i.e. greater than 1.33H, the reduced pressure zone of the obstructing building no longer appeared to affect the windward wall and in the general ventilation conditions were found to be proportional to the distance of separation. The decreased pressure to the leeward of the obstructing building was also found to be intensified by either increasing its height or its length normal to the wind. From the work of Weston shown above, the following additional comments may be made.

(i) The values of the standard deviations of the internal flow rates shown in Figure 3.1, indicate that the variation in natural ventilation conditions due to the various obstructions investigated were small (order of 5 - 10%) for any particular distance.

(ii) It is not possible to establish any meaningful relationship between the ventilation conditions and the geometry of the obstruction owing to the limited test range (see table 3.1)

3.2.2 In a series of wind tunnel experiments reported by Givoni (1968), the effect of building group geometry on natural ventilation and air flow round building blocks was investigated. In this study measurements of average air speed were made both inside and outside the models, and expressed as a percentage of the wind speed at the same height upstream of the group. As no mention was made of the mean velocity gradient in the incident flow, it is resonable to assume that the flow was uniform. The blocks which measured 600 x 200mm in plan by 400 mm heigh were arranged in either two or three rows normal to the wind. In the former arrangement in which only two blocks were used one block in each row, the longitudinal distance of separation was varied from 0.75 to 3.25H at 0.25H intervals, where H is the block height. In the latter arrangement where three rows were considered, longitudinal distances of separation took the values of 0.75H, 1H and 1.25H, while the lateral distance of separation between blocks in the same row varied from 0 to 1.25H at intervals of 0.25H. In this latter arrangement the case of a single block in each row was also studied as an extreme where the lateral distance of separation is ∞. The main conclusions obtained by Givoni, from this work were:

(i) The effect of increasing the longitudinal distance of separation between blocks in two rows was to increase the air speed between the blocks whilst the internal air speed in the leeward block reflected an initial decrease followed by an increase.

(ii) The effect of increasing the lateral distance of separation between blocks in the same row was to initially increase both internal and external air speeds then to reach a maximum followed by gradual decrease to a value approximately equal to the initial value where the lateral distance was zero.

Despite the usefulness of these results it is difficult to extend their applicability to other situations, since the values of internal air speeds given is dependent largely on the block proportions and the wall opening details, as well as the flow properties.

3.2.3 Nelson (1971) reported an algorithm for the computerized calculation of natural ventilation rates in which an equation similar in form to the equation

$$V = C_i \cdot L_c \cdot (\Delta p)^{1/n} \qquad ......(1.1)$$

was adopted. The effect of the surrounding buildings as well as the building orientation was taken into consideration for assessing wind pressure. In principle it is assumed that the pressure, P_y, acting at any height, y, on the building facade may be obtained using the following formula:-

$$P_y = K_o \, (C_{p_f} \cdot \tfrac{1}{2} \, \rho u_y^{\,2}) \qquad ......(3.1)$$

where C_{p_f} is a correction factor for the effect of surroundings and K_o is a correction factor dependent on the facade orientation. The pressure correction factor C_{p_f} is given for three types of surrounding buildings at different distances of separation, which are given in table 3.2.

Table 3.2 Values of C_{p_f} for different surrounding buildings and distances of separation

Separation distance	Lower building Upstream			Equally high or higher building Upstream			Taller building downstream		
Subject building thickness	Windward wall	Leeward wall	Side wall	Windward wall	Leeward wall	Side wall	Windward wall	Leeward wall	Side wall
0.5	0.10	−0.30	−0.80	−0.50	−0.25	−0.45	0.50	0.45	0.45
1.0	−0.10	−0.25	−0.50	−0.50	−0.20	−0.30	0.45	0.30	0.30
2.0	0.10	−0.25	−0.40	0.00	−0.20	−0.30	0.45	0.10	0.10
3.0	0.10	−0.25	−0.40	0.10	−0.20	−0.35	0.45	0.00	0.00
5.0	0.25	−0.35	−0.60	0.25	−0.25	−0.45	0.50	−0.10	−0.10
∞	0.60	−0.35	−0.70	0.60	−0.35	−0.70	0.60	−0.35	−0.70

The dynomic head $\frac{1}{2}\rho u_y^2$ was determined from a velocity profile formula similar to that used by Vincent and Bailey (equation 3.2) given in the next section. The correction factor K_o, which allowed for the variation of pressure with orientation, is assumed to be equal to −1.0 for the leeward walls, whilst for the windward walls $K_o = \text{Cos}\ \theta$ and for the side walls $K_o = -\ \text{Cos}\ \theta$, where θ is the angle between the wind and a normal to the building face. The following ranges of θ are given for each wall:

Windward wall	$315^o < \theta < 45^o$
Side Wall	$\{ 45^o < \theta < 90^o$ $270^o < \theta < 315^o$
Leeward Wall	$90^o < \theta < 270^o$

3.2.4 The following remarks may be noted on the method suggested by Nelson.

(i) The basic concept of using the dynamic head of the flow to describe the pressure on the building suggests a similarity to the concept employed in the Crack Method of the IHVE Guide. The main criticism in such a concept is that the pressure coefficient used is independent on both the building shape and the properties of the incident flow.

(ii) A closer look on the correction factor for the surrounding buildings, C_{p_f}, shows that it is actually a different way of presenting the results of Vincent and Bailey (1943) which will be commented on in the next section

(iii) The variation of the pressure correction factor, K_o, with the angle of incidence θ shows an abrupt change of sign for the same magnitude at $\theta = 45^o$ and 315^o, the angle at which the facade changes from windward to sideward. Though there will be a gradual change of sign it will not be as abrupt as this method indicates.

3.3 Previous work on wind loading on building groups

3.3.1 Vincent and Bailey (1943) carried out a series of wind tunnel experiments to investigate proximity effects on the wind loading of buildings. The cases considered were mainly for two buildings, one downstream of the other, though some additional results are given for the isolated building case and for an array of three identical buildings. All of the cases of building proximity investigated showed the effect of the obstruction by an upstream building apart from one case in which the effect of a downstream high building on a low building upstream was investigated. The geometrical variables considered in this study were the building shape, the group form and the distance of separation between buildings. In the seven shapes of buildings considered, (see table 3.3) variations were made in the height and roof shapes while the length and thickness remained approximately constant.

Table 3.3 Description of the models used by Vincent and Bailey

Model	Height to eves (mm)	Overall height (mm)	Length normal to Wind (mm)	Thickness along wind (mm)	Type of Roof
A	30.5	42.7	127	53.8	Sloped at 23.5°
B	30.5	58.7	127	53.8	Sloped at 45°
C	63.5	91.7	127	53.8	Sloped at 45°
D	30.5	46.7	127	53.8	Sloped at 30°
E	30.5	31.2	127	53.8	Flat
F	63.5	64.3	127	53.8	Flat
G	-	132.1	203.2	50.8	Stepped

The distance of separation was varied in units of the building thickness, from a minimum of zero to a maximum which varied from 3 t 20 for different models. Despite the early date of this report, consideation was given to the simulation of the natural wind profile at least in terms of velocity gradient. The profile simulated was that appropriate to flow in open country with a boundary layer thickness, δ, of 203mm. The profile shape was a close approximation to the following formula, suggested by the Meteorological Office at the time.

$$\frac{u_y}{u_{10}} = K\{1.00 + 2.81 \log (y + 4.75)\} \qquad ......(3.2)$$

No mention was made of the method by which the velocity profile was simulated. In the course of this investigation pressure measurements were obtained from a centre line row of tappings of the windward wall and the roof. The leeward wall pressure was obtained from only one tapping near the top of the wall. The pressures were given in the form of coefficients non-dimensionalized with respect to the dynamic head at a height of 50.8mm from the tunnel wall. From the results obtained, those concerning the wall pressures are considered most relevant and are shown in Figure 3.2 (a) - (j). For convenience of comparison and analysis, the variation of mean pressure on both walls with distance of separation have been replotted together with the corresponding values for the isolated test building in each case. The main conclusions drawn by Vincent and Bailey from this study were:

(i) The effect of a small building on the pressure difference across a heigh building downstream, case (a), is small. The maximum reduction at any distance was about 20% of the isolated case.

(ii) In the case of two high buildings, case (b), a considerable effect on the wall pressures was found

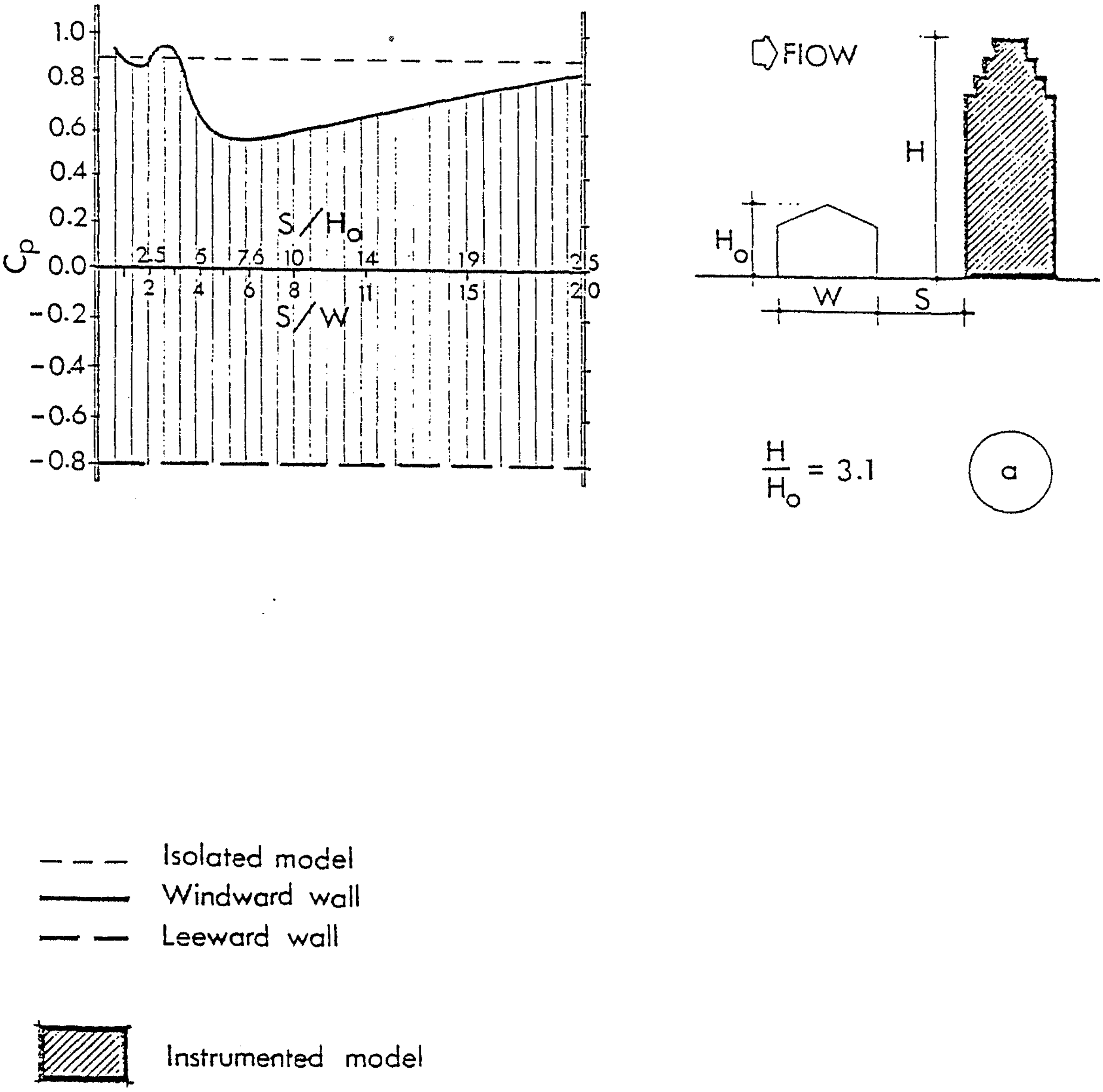


Figure 3.2 VINCENT AND BAILEY'S RESULTS, (adapted from Vincent and Bailey, 1943).

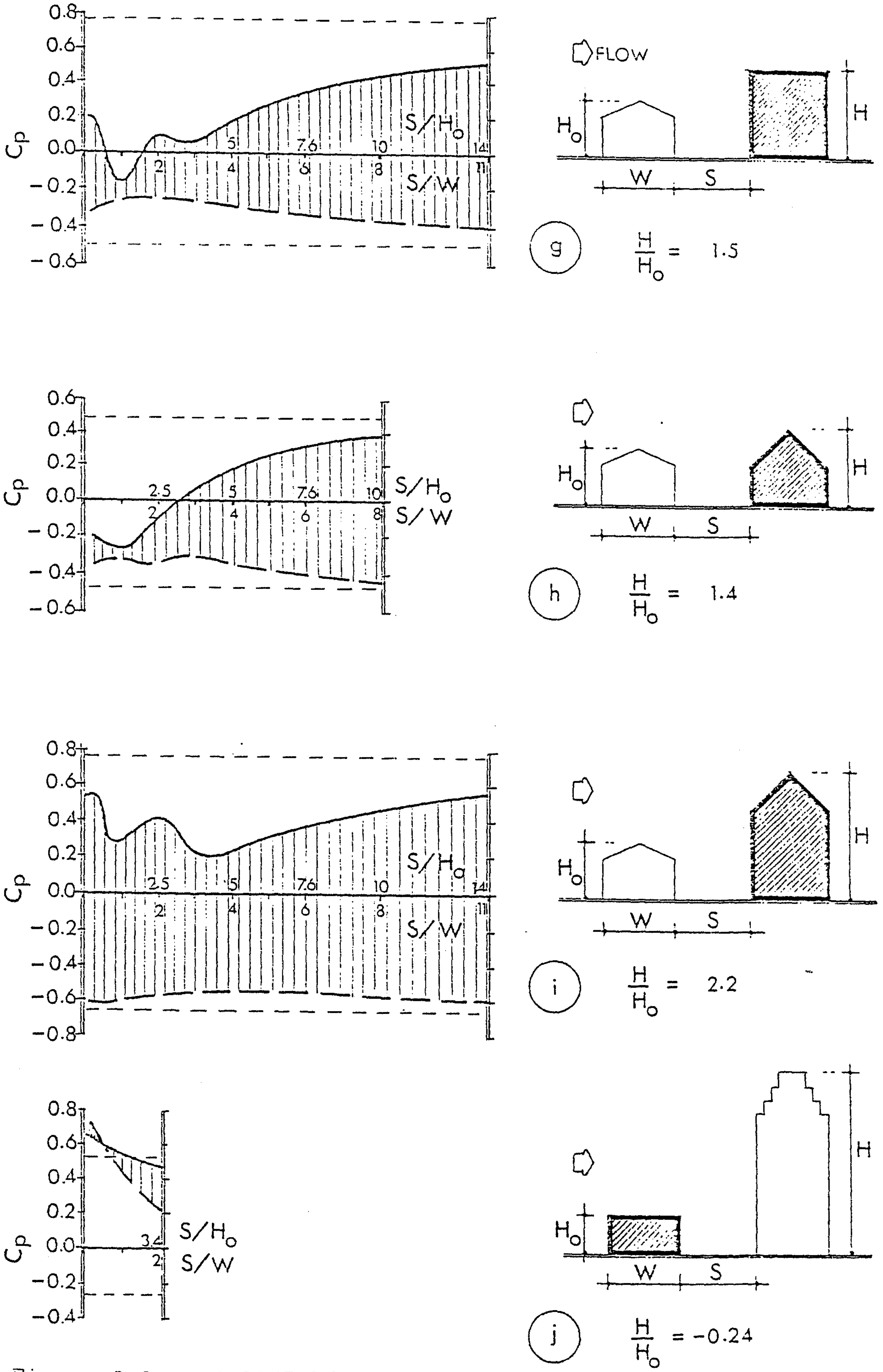


Figure 3.2 VINCENT AND BAILEY'S RESULTS, (adapted from Vincent and Bailey, 1943).

For legend see Figure 3.2(a)

to occur as the distance of separation decreased. The pressure difference between the windward and leeward walls was zero at a distance of separation 6 times the building thickness. Furthermore, thrust forces, where the windward wall pressures were more negative than those on the leeward wall, were experienced at smaller separation distances.

(iii) The effect of the number of models upstream, cases (c) and (d), was found to be small, therefore, the results would be expected to be representative of built up areas.

(iv) Due to the downwind shelter effect present in most cases even at large separation distances, allowance should be made to reduce the fully exposed values for the lower part of a building up to some specific height.

3.3.2 From a further consideration of the results obtained by Vincent and Bailey the following points emerged:-

(1) For the two building cases it can be shown that the variation of wall pressure with distance of separation in the different cases depends on group form. Suggesting H/H_o as a parameter roughly describing group form, (where H is the height of the building under investigation and H_o is the height of the obstructing building) different group forms regardless of roof shape may be written as:-

(i) $H/H_o < 1$, high building upstream

(ii) $H/H_o = 1$, two equal buildings

(iii) $H/H_o > 1$, low building upstream

A negative sign may be given to this parameter to indicate a reverse situation when the building under consideration is upstream of the obstructing building. An example of this case was included in the study and the result is shown in case (j).

2. In case of more than two buildings additional geometrical parameters are needed to describe the group form, where variations in individual building dimensions will add complexity to these parameters. Here only one simple case has been considered, case (d) where the three buildings tested were identical.

3. A zone of negative pressure difference at certain distances of separation can be seen as a common feature in the cases of Figure 3.2 (b), (c), (e) and (f). The significance of this observation is that these are the only cases where $H/H_o \leqslant 1$. Furthermore, the distance at which the pressure difference changes its sign appears to be approximately the same in all those cases apart from case (b). However, normalizing the distance of separation with respect to H_o rather than the building thickness, is not only more appropriat because of the sensitivity of flow to variation in height but also makes the separation distance at which zero pressure difference occurs approximately equal in all cases.

4. In the cases where $H/H_o > 1$ i.e. cases (a), (g), (h), and (i), the pressure difference between the windward and leeward faces was positive at all distances, and the shelter effect decreased as H/H_o increased.

5. Finally, a relevant point may be made concerning the case of more than two buildings shown in case (d). Here, contrary to the conclusion given in the paper which implies a negligible effect for the number of models, it can be seen by comparing cases (c) and (d) that two major differences occur. First, the zone of negative pressure difference which was dominant in the two building case, (c), disappeared in the three building case, (d); and secondly, the point at which the pressure difference is zero occurs approximately at zero distance of separation.

3.3.3 The general conclusions which could be obtained from Vincent and Bailey's work are:

1. The parameters governing the flow and pressures in groups of two buildings are not the same as those for an array of more than two.
2. For pairs of buildings subject to the same incident flow conditions, the pressure difference between the windward and leeward faces was affected both by the building form and the distance of separation. Better correlation of the results was obtained whe the group form parameter H/H_o was used and when the distance of separation was normalized with respect to H_o rather than the building thickness.

3.4 Previous work on air flow round groups of buildings

3.4.1 Wise, Sexton and Lillywhite (1965) have reported some measurements of the flow round buildings on the basis of wind tunnel experiments. The building types under investigation consisted of a low rise building, a tower building and a slab building. The dimensions of these models in terms of the low rise building height are given in table 3.4.

Table 3.4 Dimension of the models used by Wise et. al (1965) in terms of the low rise building height

Model	Height, H	Length	Thickness
Tower	4	1	1
Slab	3	4	1
Low building	1	4	1

where the length is the dimension normal to the flow and the thickness is the in-wind dimension. The incident flow simulated a suburban velocity profile artificially generated using vertical array of horizontal slats. The buildings were relatively large in size compared with the boundary layer thickness, δ, i.e. $H/\delta = 0.22, 0.67, 0.89$ for the low building, the slab and the tower respectively. Three forms of building groups were studied in addition to the isolated building cases, in which the air velocity was measured at discrete points round the blocks. The groups considered were: (i) two low buildings, (ii) three low buildings and (iii) a slab with a low building upstream. In all cases the distance of separation was kept constant at double the low building height. The results showed that a vortex existed between the buildings in all cases. However, the wind speed at any point between the buildings compared with that at the same height far upstream is shown to be reduced in between the buildings in cases (i) and (ii) whilst in case (iii) it increased by about 30% in the region close to the ground. Furthermore, it was noted that the effect of adding the third building, case (ii), on the relative speeds observed in the two building group, case (i), was negligible. An examination of the data presented here does not, however, yield the information that the relative speed between building 1 and 2 (the upstream pair) is 30% less than that between buildings 2 and 3 (the downstream pair) in case (ii). The particular geometric parameters considered in the work of Wise et.al coupled with the relaxation of simulating size parameters, i.e. H/δ or H/Z_o will tend to limit the general applicability of the results. In addition, the flow speed measurement at discrete points makes it difficult to obtain any relation between the flow parameters and the group form parameters.

3.4.2 In order to relate the flow speed at one point to the geometrical parameters describing a group of two buildings, Wise (1970), in a later investigation, carried out a more detailed study of case (iii), the combination of a slab with an upstream low rise building. The geometrical parameters varied were: the distance of separation, L_x, the slab building thickness, W, and the slab building height H. The main conclusion reached was that the velocity at one point between the two buildings and close to the ground, u_A is a complex function of the wind speed at the top of the slab building, u_H; the height of the point above the ground, a; the slab building length, L, height, H and thickness, W; as well as the low building height h. The following expression was obtained for u_A.

$$\frac{u_A}{u_H} = 0.24 \{ (\frac{a}{H})^{0.28} + (\frac{L}{H})^{0.4} (\frac{W}{H})^{0.4} (\frac{H}{h})^{0.8} \} \quad ......(3.3)$$

This equation was found to be applicable within the following limits only $\frac{H}{a} > 33$, $\frac{W}{H} > 1$, $\frac{L}{H} > 1$ and $\frac{H}{h} > 8$.

3.4.3 In a study, whose purpose was to improve the natural ventilation rates of low rise housing in different layout patterns, Olgyay (1963) presents a series of useful flow visualization photographs. The group model consisted of six blocks, arranged in three rows at different spacing in each layout pattern. The main conclusion resulting from this study was that the gridiron pattern (where buildings are aligned in the wind direction) causes more shelter to subsequent rows of buildings, while the staggered pattern (where buildings are shifted laterally every other row) gives better ventilation. It was recommended that a spacing of seven times the building height should secure satisfactory ventilation for each unit. Similar comments are given in the book by Koenigsberger, Ingersoll, Mayhew and Szokolay, (1973) in a series of sketches which were based on studies carried out in the A.A. school of Architecture. Here, a distance of six times the building height is given as the satisfactory limit for an adequate natural ventilation.

3.4.4 In the studies of Olgyay and Koenigsberger, et. al the measure of satisfactory ventilation was not defined, nor was the form of the indivdual buildings considered to be an important parameter. The effect of the latter is expected to play an important role and such recommendations as they give should be treated with caution.

3.5 Conclusions

3.5.1 From the above review, the following conclusions may be drawn:

1. The flow and the pressure forces on groups of buildings are dependent on both the individual building form, i.e. size and shape and the building group form, i.e. the relative size of individual buildings and the layout pattern.
2. The simulation of the natural boundary layer properties in terms of the velocity profile shape was considered by some workers. However the effect of building size in terms of H/δ or H/Z_o was not considered at all.
3. The effect of fetch on either the flow or the drag forces was not considered at all.
4. Despite the useful information obtained from the work on natural ventilation, wind loading and wind flow round groups of buildings, no general relationship was obtained between the group geometry the resulting flow and the pressure forces. This

conclusion is natural as the number of variables involved is prohibitively large and any general relationship would be a complex one.

5. It is evident that the pressure forces on a group of two similar buildings, hence the flow, does not represent the flow round a group of more than two buildings, the case of urban areas.

3.5.2 The complexity of the problem indicated by the above conclusions suggest that in order to obtain any relationship between individual building form, building group form and the resulting pressure forces, great limitations ought to be put to the variables involved, and in particular those concerning the building and group form. A more appropriate approach may then include the effect of building size, (H/δ), as well as the size of the building group (in terms of fetch) required to give representative results of the corresponding conditions in urban areas.

CHAPTER 4

DENSITY AND FORM

4. DENSITY AND FORM

4.1 Introduction

4.1.1 The design and planning of residential areas often refers to housing density as an indicator of environmental quality. This follows from the hypothesis that the geometry of urban form will largely determine its environmental conditions. Since the density of built form is a function of its geometry it is important to determine the relation between the geometrical parameters needed to define group form and its density.

4.1.2 Several studies have been made in which the density of residential areas were considered in relation to planning parameters as well as geometrical parameters for different environmental criteria. A review on these studies is made in order to see how accurately group form can be defined in terms of the parameters considered, as well as to determine the practical limits of these parameters. A theoretical analysis is also presented to enable a complete definition of group form to be made, in terms of a proposed set of geometrical parameters and group density.

4.1.3 Due to the complex interaction between the parameters involved, a method of graphical presentation has been evolved to show the interaction between these parameters, as well as the commonly accepted zones confined within their limits. If flow conditions are dependent on group form then the suggested graphical presentation would help in identifying zones of similar flow conditions. Such an identification procedure will not only help the planner in recognizing the consequences of form variation on the resulting flow, but also would guide the aerodynamicist to design meaningful experiments within the practical limits of urban form.

4.2 Density of Residential Areas

4.2.1 The density of residential areas has been investigated from many different aspects and for various criteria, Gropius (1956), Stevens (1960), Segal (1965) and Martin and March (1972). The large number of the variables involved coupled with the interrelationship existing between them, make it necessary to clarify the concept of density. It is of particular importance to identify the relevant parameters linking the planning and aerodynamic aspects of urban building density.

4.2.2 For provision of sunlighting, Gropius considered the problem as a two dimensional building array and investigated the following variables:

site area/building	A
angle of sunlighting	γ
number of beds	N
number of storeys	F

His conclusions were reported by Martin et. al. (1972) in which the following relationships were suggested:

(i) N increases as F increases when A and γ are constant.

(ii) A decreases as F increases when N and γ are constant.

(iii) γ decreases as F increases when A and N are constant.

Although these relationships considered descriptions of form, they are neither conclusive nor do they recommend the limit of each variable. Moreover, the relations are not presented in a manner which quantifies the extent to which these variables are inter-dependent.

4.2.3 In his study, Stevens (1960) was concerned with the aspect of population density in residential areas. Although some of the parameters he considered affect the group form (e.g. number of storeys and plot coverage), the way in which the charts and tables supplied are presented does not convey how different geometrical forms are utilised for the same population density. Furthermore the range of these parameters is limited, i.e. the numbers of storeys considered were 1, 2, 4, 8 and 12.

4.2.4 The analytical approach taken by Segal (1965) considered the following variables:

1. Floor space rate (unit area/person)
2. Floor space/dwelling (dwelling area)
3. Angle of obstruction
4. Open space area/dwelling
5. Storey height
6. Site area
7. Number of storeys
8. Ground coverage (area density)
9. Number of dwellings

He noted that if the first five variables are kept constant then by increasing the number of storeys the resulting changes to the remaining variables were as follows:

(i) The site area/dwelling decreased,

(ii) the site coverage/dwelling decreased,

(iii) the number of dwellings/acre increased.

However, the rate of decrease or increase is negligible as the number of storeys increases reaching an optimum value between 10 - 15 storeys. These results are helpful in determining the geometrical configuration of a group of houses, However, some of the parameters which were maintained as constants, i.e. the angle of obstruction and the open space area/unit floor area, are of considerable influence on the grouping form; thus restricting the scope of Segal's conclusions.

4.2.5 Svennar (1972) discussed the viability of 14 parameters used in studying the density of residential areas, and proposed a standard set of parameters (Table 4.1) differentiating between those related to density and those related to space. Either group of parameters could be expressed in terms of floor area, dwelling units or population.

Table 4.1 Density and space parameters proposed by Svennar (1972)

	Density	Space	
		Indoors	Outdoors
Floor area	Floor Space Index $= \frac{\text{gross floor area}}{\text{gross site area}}$	Open Space Index $= \frac{\text{free site area}}{\text{gross floor area}}$	
Dwelling Units	Housing density = dwelling units/ dekare	Unit size = gross floor/ unit	Free area/ unit
Population	Population density = persons/dekare	Floor space rate = gross floor/person	Free area/ unit

In these parameters four independent variables were considered:

λ_p = fraction of site area used for building; %
(plan area density)

F = average number of floors

Z = average dwelling unit size

G = average number of people per unit

For a given building site area, A, the following function were derived:

$$\text{Floor Space Index (F.S.I)} = \frac{\frac{\lambda_p}{100} . A . F}{A}$$

$$= \frac{\lambda_p . F}{100}$$

$$\text{Open Space Index (O.S.I)} = \frac{A - \frac{\lambda_p . A}{100}}{\frac{\lambda_p}{100} . A . F}$$

$$= \frac{100 - \lambda_p}{\lambda_p \; . \; F}$$

$$\text{Housing Density} = \frac{\frac{\lambda_p}{100} . A . F . \frac{1}{Z}}{A}$$

$$= \frac{\lambda_p \; . \; F}{100 \; Z}$$

$$\text{Free Area per unit} = \frac{A - \frac{\lambda_p . A}{100}}{\frac{\lambda_p}{100} . \frac{A \; . \; F}{Z}}$$

$$= \left(\frac{100 - \lambda_p}{\lambda_p \; . \; F}\right) . \; Z/\text{unit}$$

$$\text{Population Density} = \frac{\lambda_p \; . \; F \; . \; G}{100 \; Z}$$

$$\text{Floor Space Rate} = \frac{Z}{G}/\text{person}$$

$$\text{Free Area per Person} = \left(\frac{100 - \lambda_p}{\lambda_p \cdot F}\right) \frac{Z}{G}/\text{person}$$

From a geometrical approach it appears that the expression of both the density and the space parameters are more relevant in terms of floor area. For each function a table was supplied for different values of the four independent variables. These values ranged between:

5% - 40% for λ_p

1 - 12 for F

0.05 - 4.8 for F.S.I.

0.1 - 19 for O.S.I.

Although the requirement for sunlighting and its dependence on site latitude was noted, the variation of density with the angle of obstruction was not considered. The final part of Svennar's work dealt with an analysis of 19 residential developments of different types from which measurements of density parameters have been taken.

4.2.6 Martin and March (1972) analysed two mathematical models, the first based on Gropius's hypothesis (1956) and the second based on the work of Beckett (1942). In Gropius's model the dependent variables are:

N = number of beds

A = area of site

T = tangent of the angle of sunlight, γ.

In each of the following equations one of these variables is the dependent variable while the others are assumed constant. The remaining parameters are (see Figure 4.1(a)):

L = length of block

W = width of block (assumed to be constant)

S_x = width of site

S_y = length of site

$(S_x - W)$ = space between blocks

h = storey height (assumed to be constant)

g = parapet height (assumed to be constant)

b = number of beds per unit floor area (assumed to be constant)

The principal independent variable is:

F = number of storeys

The three experessions derived from Gropius's model are

$$N = \emptyset_1 F = bWAT . \frac{F}{hF + WT + g}$$

$$A = \emptyset_2 F = \frac{N}{bWT} . \frac{hF + WT + g}{F}$$

$$T = \emptyset_3 F = \frac{N}{W} . \frac{hF + g}{bAF - N}$$

The first derivatives $\frac{d\emptyset n}{dF}$ were obtained and are shown graphically in Figure 4.1(b), (c) and (d). It can also be shown that:

$$hN - bWAT = 0 \quad \text{when } F \to \infty$$

The second derivative of $\emptyset_1 F$ which shows the rate of increase of N decreased very rapidly (i.e. $\frac{d^2N}{dF} \propto \frac{1}{F^3}$)

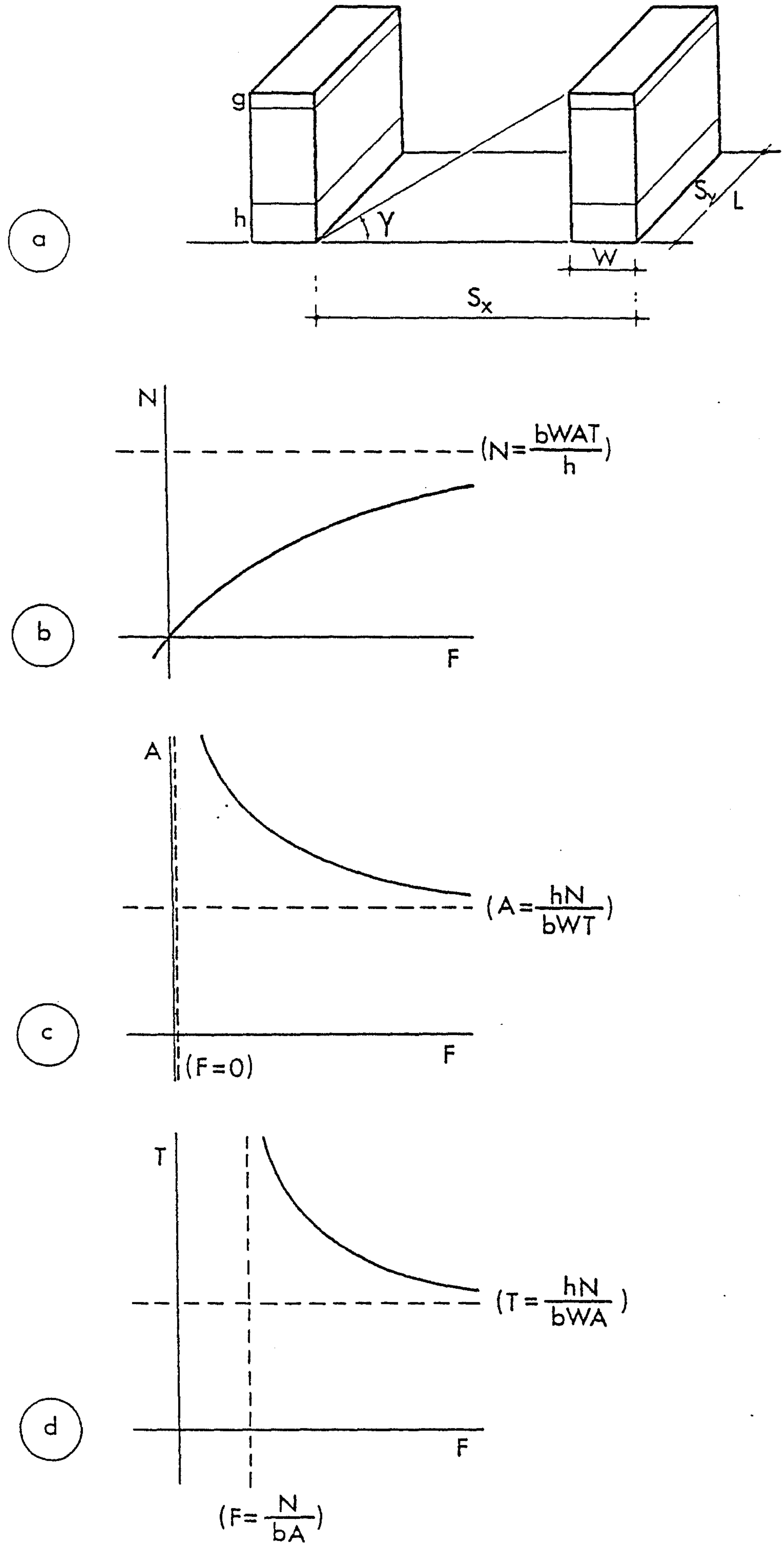


Figure 4.1 GRAPHICAL PRESENTATION OF GROPIUS'S MODEL, (after Martin and March, 1972).

4.2.7 The mathematical model of Beckett is more elaborate and refine form of Gropius's model, and differs in the following respects:

(i) The blocks were arranged in parallel rows with intersecting streets.

(ii) The angle of obstruction is read from a point above the ground on the window sill of the first floor, see Figure 4.2.

The same notation as Gropius's model is used here with the following additions:

i = height at which the angle of obstruction intersects the facade ($0 < i < h$)

$\psi_y = \frac{L}{S_y}$

O = area of open space

The principal dependent variables studies by Beckett were:

G_1 = N/A = bed space (population, etc.) density in relation to site area

$G_2 = O/A = (1 - \lambda_p)$

$G_3 = G_1/G_2 = \frac{1}{\text{Open Space Index}}$

Figure 4.3 shows the variation of G_1, G_2 and G_3 with F, for different values of T for b = 1, $\psi_y = 0.75$, i = 0.6 h, g = 0.3h. Here it should be noted that Beckett actually studied G_2/G_1 which is the Open Space Index. For small number of floors G_1 and G_3 change their behaviour for small and large values of T respectively. This contradicts Gropius's model and is mainly due to changing the point at which the angle of obstruction is measured. Martin and March conclude that for practical purposes Gropius's

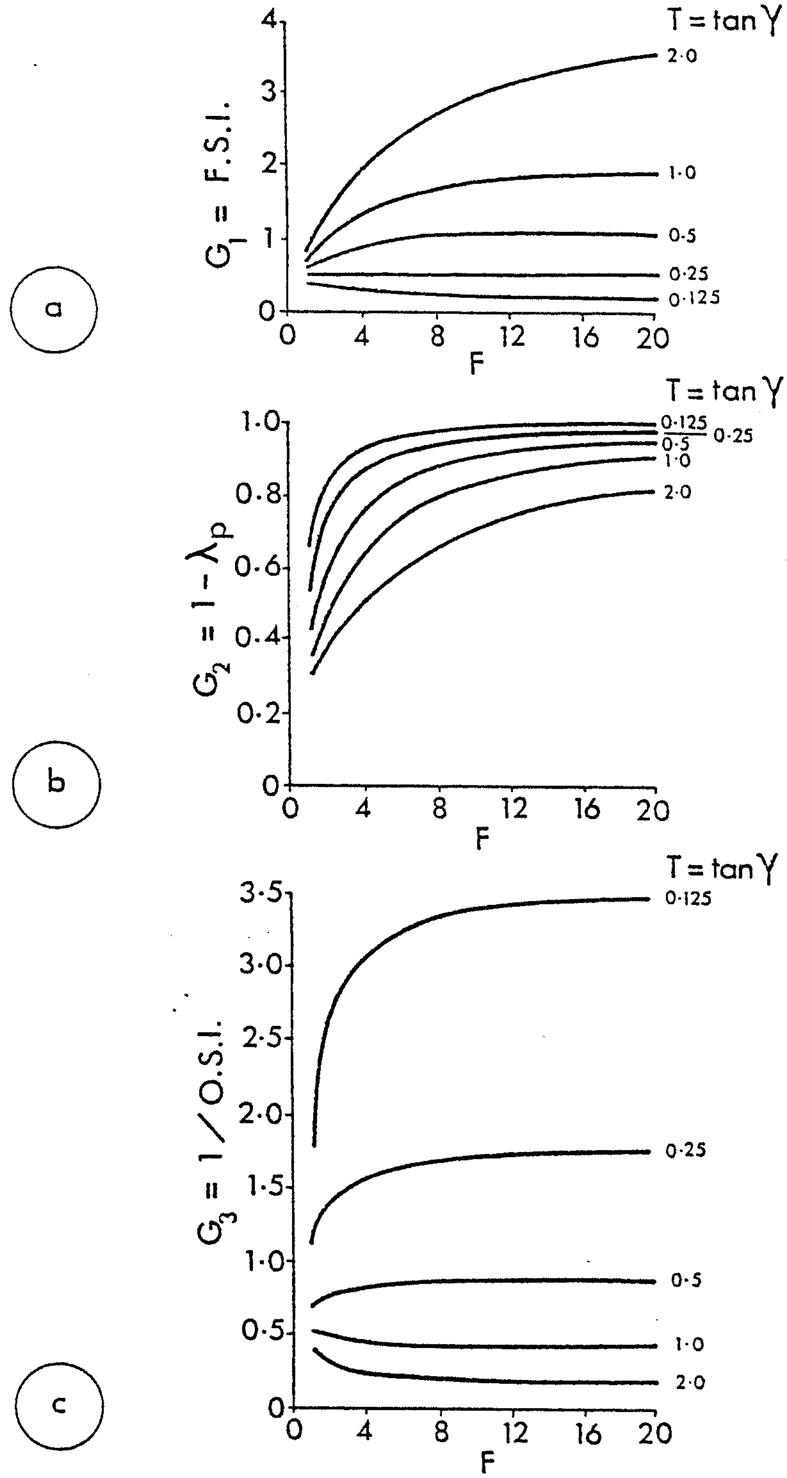


Figure 4.3 GRAPHICAL PRESENTATION OF BECKETT'S MATHEMATICAL MODEL, (after Martin and March, 1972).

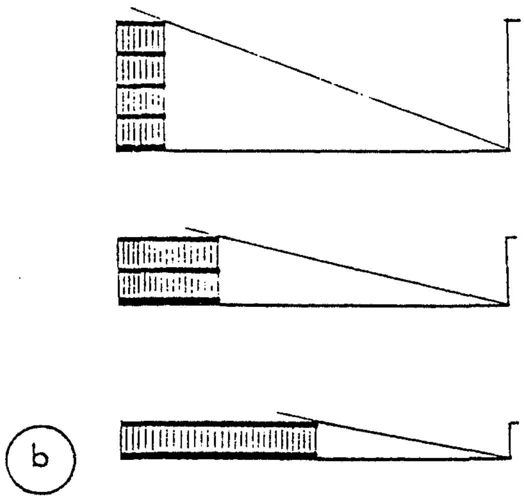
model is probably as good as Beckett's and is simpler to use. Recent investigations on daylighting suggests that the choice of reference point makes very little difference to the value of the external daylight factor and thus the angle of obstruction.

4.2.8 This review of the various methods of defining housing densities suggests the following:

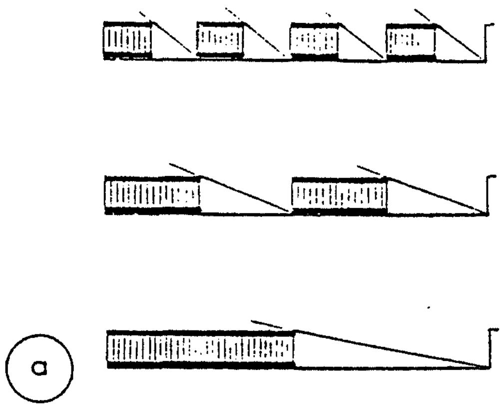
(i) For a given site area, A, and constant storey height, h, the F.S.I. determines the total volume of building(s), see Figure 4.4(a). Further knowledge of the O.S.I. helps in determining number of storeys, F, and the plan Area Density, λ_p, see Figure 4.4(b). Although a complete definition of density and space is achieved in terms of floor area, further information is needed to determine the building group form.

(ii) The angle of obstruction, γ, (on the assumption of a regular array of uniform buildings on a grid) together with the F.S.I. and the O.S.I. might be sufficient for the assessment of some urban environmental conditions, i.e. daylighting or sunlighting. However, different forms which fulfil these conditions would behave differently in aerodynamic terms, see Figure 4.4(c).

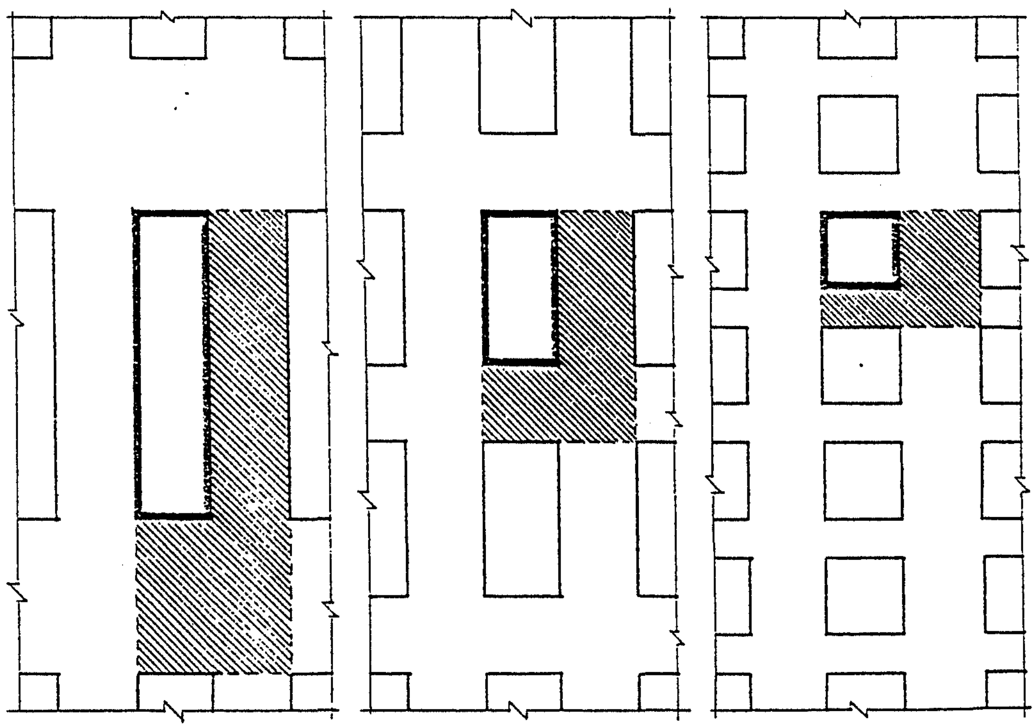
(iii) Most of the investigations considered the number of storeys as the main independent variable while other parameters relevant to air flow were either not considered in depth (i.e. the plan area densit



F.S.I. only is constant; O.S.I., F, λ_p, γ and A_s are variables.



F.S.I., O.S.I., F and λ_p are constant while A_s and γ are variables.



F.S.I., O.S.I. and γ are equal in all configurations despite their differences in group form.

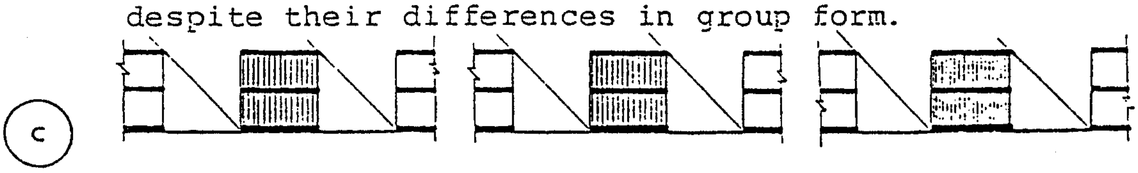


Figure 4.4 EFFECT OF INCOMPLETE DEFINITION OF FORM DETERMINING PARAMETERS.

$\frac{\text{Building plan area}}{\text{Building site area}}$) or not considered at all.

(i.e. the Frontal Area Density, $\frac{\text{Building facade area}}{\text{Building site area}}$,

Side Aspect Ratio, $\frac{\text{Building thickness}}{\text{Building height}}$, and Frontal

Aspect Ratio, $\frac{\text{Building length}}{\text{Building height}}$).

(iv) As the parameters are interdependent a representation more suitable than tables (Svennar), and more compact than several graphs (Martin and March), on which the range and limits of all the relevant variables could be seen, is desirable. Furthermore it is apparent that density limits depend on the criterion considered. This criteria in turn selects or may sometimes introduce its own governing parameters. For example the form determining parameters for daylighting would not consider orientation while for sunlighting, orientation and latitude would be important. Considering boundary layer flow over urban areas, the group form determining parameters may be selected so as to be more oriented towards flow criteria. No such attempt has been previously undertaken.

4.3 The geometrical parameters defining group density and form

4.3.1 An attempt is made here to analyse the density of urban building form which overcomes some of the criticisms of previous work reported in the preceding section. With particular reference to air flow over building groups, it is expected that a complete definition of group form would include the geometrical parameters of the individual buildings as well as those of the group. For rectangular building forms, uniformly distributed on a grid pattern, see Figure 4.5, the following parameters are chosen.

(i) Individual form parameters

- h = storey height
- F = number of storeys
- H = building height (= F.h)
- L = building length (across flow direction)
- W = building thickness (along flow direction)
- a_p = building plan area (= L.W)
- a_f = building facade area (=L.H)
- A_f = frontal aspect ratio = $\frac{L}{H}$
- A_s = side aspect ratio = $\frac{W}{H}$
- W_r = floor width ratio = $\frac{W}{h}$

(ii) Group form parameters

- S_x = building site length (in the flow direction)
- S_y = building site width (across flow direction)
- A = building site area (= $S_x.S_y$)
- γ_x = angle of obstruction (in the flow direction)
- γ_y = angle of obstruction (across flow direction)

$$\tan \gamma_x = \frac{\text{building height}}{\text{longitudinal space between buildings}} = \frac{H}{S_x - W}$$

$$\tan \gamma_y = \frac{\text{building height}}{\text{lateral space between buildings}} = \frac{H}{S_y - L}$$

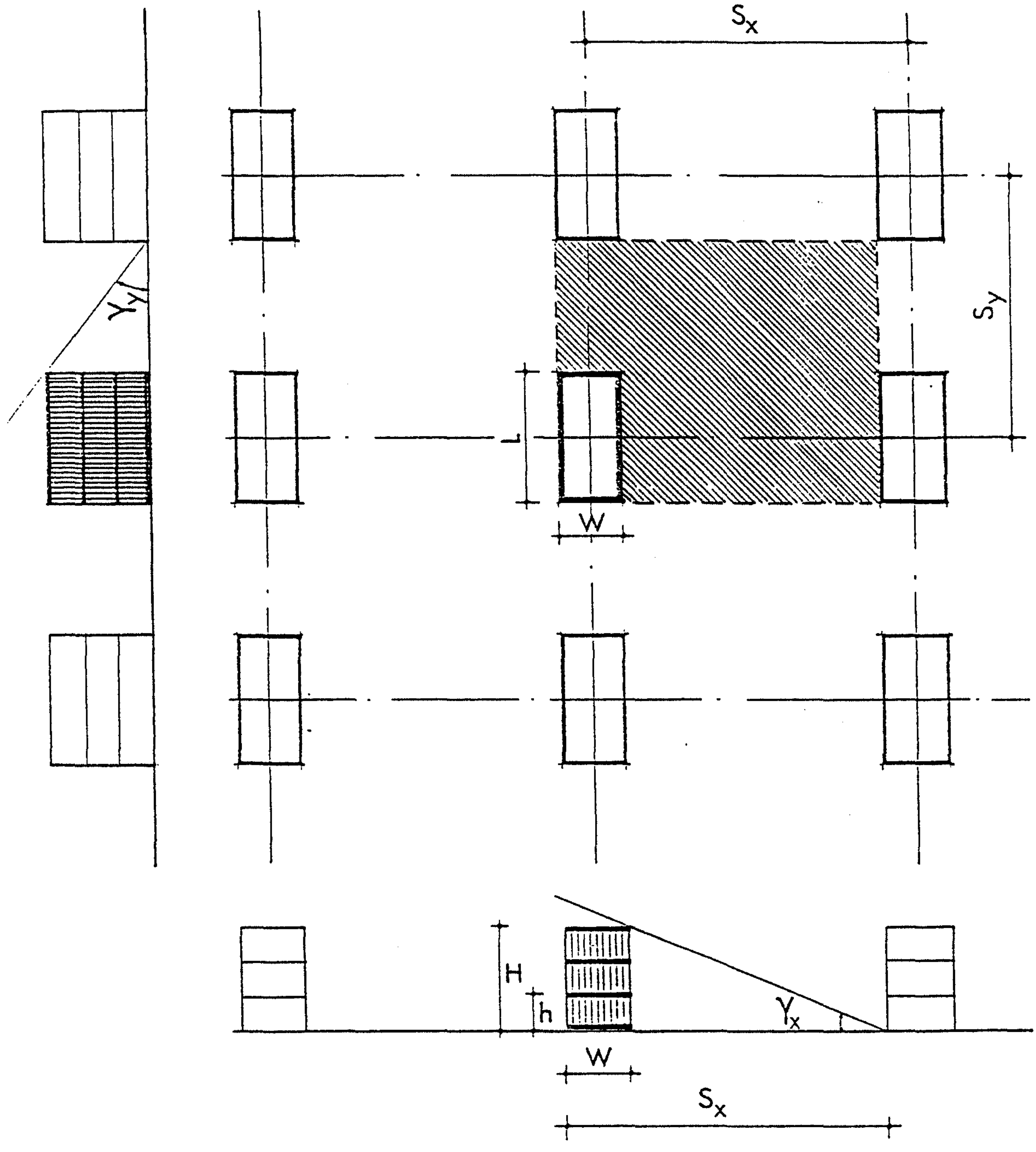


Figure 4.5 GENERAL GROUPING FORM AND
ITS GEOMETRICAL PARAMETERS.

$$\psi_x = \frac{\text{building thickness}}{\text{building site length}} = \frac{W}{S_x}$$

$$\psi_y = \frac{\text{building length}}{\text{building site width}} = \frac{L}{S_y}$$

$$\lambda_p = \text{plan area density} = \frac{\text{building plan area}}{\text{building site area}} = \frac{a_p}{A}$$

$$\lambda_f = \text{frontal area density} = \frac{\text{building facade area}}{\text{building site area}} = \frac{a_f}{A}$$

$$\therefore \quad \lambda_p = \lambda_f . A_s$$

4.3.2 It is shown in paragraph 4.2.8(i) how the planning parameters (F, F.S.I and O.S.I) are not sufficient to define a particular group form. However, they may be expressed in terms of the geometrical parameters as follows:-

$$\text{F.S.I} = \text{Floor Space Index} = \frac{\text{total floor area}}{\text{building site area}} = \frac{a_p F}{A}$$

$$\text{O.S.I.} = \text{Open Space Index} = \frac{\text{open space area}}{\text{total floor area}} = \frac{A - a_p}{a_p F}$$

Similarly, these planning parameters are related to the plan area density as follows:

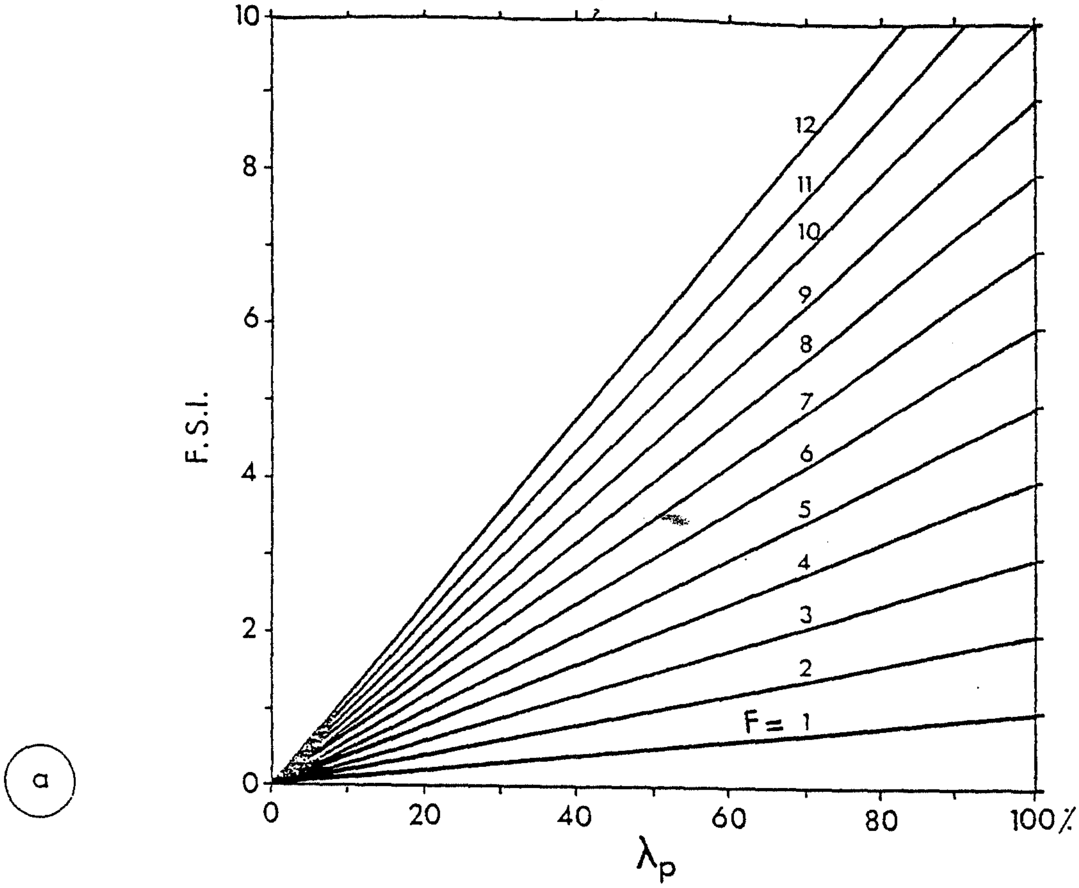
$$\text{F.S.I} = F.\lambda_p \qquad \ldots\ldots \qquad (4.1)$$

and $$\text{O.S.I} = \frac{1}{\text{F.S.I}} (1 - \lambda_p)$$

This may be re-arranged into:

$$\text{F.S.I} = \frac{1}{\text{O.S.I}} (1 - \lambda_p) \qquad \ldots\ldots \qquad (4.2)$$

A graphical presentation of equation (4.1), Figure 4.6(a), gives a family of straight lines, the slope of each line would correspond to the number of storeys. In the same way, a graphical presentation of equation (4.2), Figure 4.6(b), gives a family of straight lines, the slope of each line would correspond to the reciprocal of O.S.I.



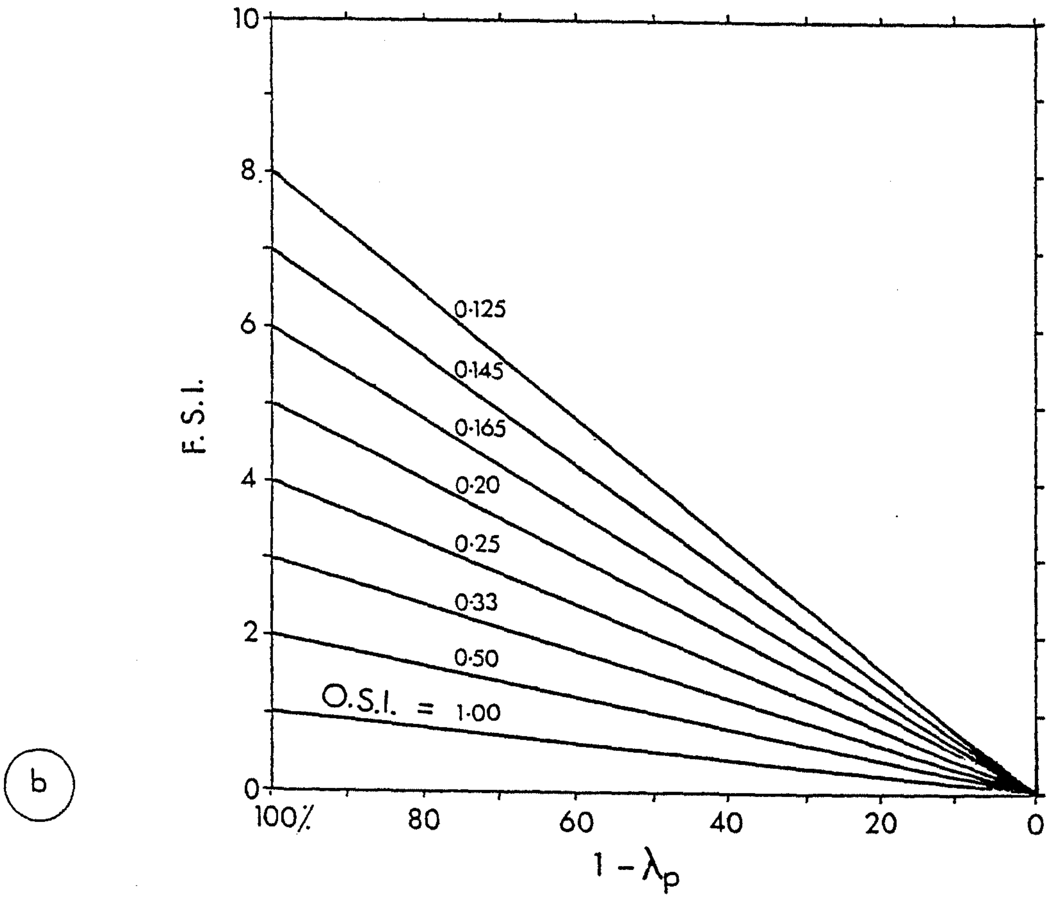


Figure 4.6 (a) VARIATION OF F.S.I. WITH λ_p FOR DIFFERENT NO. OF STOREYS.
(b) VARIATION OF F.S.I. WITH OPEN SPACE BETWEEN BUILDINGS FOR DIFFERENT VALUES OF O.S.I.