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Publisher's version / Version de l'éditeur:

ASHRAE Transactions, 85, 1, pp. 72-84, 1979

National Research Council of Canada

Conseil national de recherches du Canada

A METHOD FOR PREDICTING AIR INFILTRATION RATES FOR A TALL BUILDING SURROUNDED BY LOWER STRUCTURES OF UNIFORM HEIGHT

by C. Y. Shaw

Reprinted from
ASHRAE Transactions
Vol. 85, Part 1, 1979
p. 72 - 84

DBR Paper No. 890
Division of Building Research

Price $1.25 OTTAWA NR CC 18029

SOMMAIRE

Etant donné l'augmentation rapide du coût de l'énergie et le besoin pressant d'une utilisation rationnelle, de nombreux édifices sont analysés en fonction de leur efficacité énergétique au moyen de programmes informatiques sophistiqués. Un des problèmes inhérents à ces programmes est l'absence d'une méthode précise mais simple pour évaluer le taux d'infiltration d'air, qui est un des facteur importants de la consommation d'énergie. Afin de mettre au point une telle méthode, l'auteur a effectué une étude informatique des caractéristiques de fuite d'air des édifices en hauteur à l'aide de données sur la pression du vent en surface obtenues dans une soufflerie (couche limite). L'auteur présente de nouvelles données de distribution de la pression sur les faces d'un édifice en hauteur entouré de constructions plus basses de hauteur uniforme. L'édifice étudié et les construction avoisinantes sont séparés par l'équivalent d'une rue avec trottoirs.

Des équations pour la prédiction du taux d'infiltration de l'air ont été dérivées. Ces équations ne sont valables strictement que pour les édifices en hauteur entourés de constructions plus basses,de hauteur à peu près uniforme. Les équations ne peuvent être généralisées pour un grand édifices protégé par un autre grand édifice à moins que ceux-ci ne soient assez éloignés l'un de l'autre.

No. 2514

A METHOD FOR PREDICTING AIR INFILTRATION RATES FOR A TALL BUILDING SURROUNDED BY LOWER STRUCTURES OF UNIFORM HEIGHT

C.Y. SHAW

INTRODUCTION

With the rapidly rising energy costs and a growing need to conserve energy, more and more buildings are being analyzed for energy effectiveness using sophisticated computer programs. One problem inherent in these programs is the lack of an accurate but simple method for estimating air infiltration rate, which is known to be a significant component of the energy consumption. To develop such a method, a computer study of air leakage characteristics was made for tall buildings using surface wind pressure data obtained in a boundary layer wind tunnel. The results for a fully exposed tall building in a suburban area were reported by Shaw and Tamura (1). This paper presents new data on pressure distributions over the faces of a tall building surrounded by lower structures of uniform height. The building and the surrounding structures are separated from each other by a distance equivalent to that of a street and sidewalks.

Equations for predicting air infiltration rate have been derived using basically the same method as in the paper for fully exposed tall buildings (1). These equations are strictly valid only for a tall building surrounded by lower structures of approximately equal height. They may not be generalized for a tall building partially protected by another tall building unless the buildings are sufficiently far apart.

FACTORS GOVERNING AIR INFILTRATION

Air infiltration is the leakage of air through cracks and openings that exist in a building envelope. Its magnitude can be calculated from

$$Q = C_j \, A_j \, (\Delta P_j)^{0.65} \qquad (1)$$

where

Q = air leakage rate

C_j = leakage coefficient of a building component per unit area

ΔP_j = pressure difference across an opening

A_j = area of the building component

The leakage coefficient for a building can be best estimated from the results of air leakage measurements conducted on similar type buildings. For tall buildings, the suggested values are given in Table 1 (2, 3, 4).

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TABLE 1

Leakage Coefficients for Building Components

	Leakage Coefficients	Correction Factor for C_w
Curtain Wall	C_w, $m^3/s \cdot m^2 \cdot Pa^{0.65}$	$\alpha_w = C_w/(C_w)_{avg}$
Tight	0.31×10^{-4}	1/3
Average	0.93×10^{-4}	1
Loose	1.83×10^{-4}	2
Floor	C_f, $m^3/s \cdot m^2 \cdot Pa^{0.5}$	
Average	5.3×10^{-5}	
Shaft/Story		
Elevator	C_s/car, 0.075 $m^3/s \cdot Pa^{0.5}$	
Stair	C_s/shaft, 0.03 $m^3/s \cdot Pa^{0.5}$	

The pressure difference across a building envelope depends on inside-outside temperature difference, amount of pressurization produced by HVAC systems and wind pressures on exterior walls. The first two factors can always be estimated but the third one, at present, can only be obtained experimentally. To provide the necessary wind pressure data for this study, the National Aeronautical Establishment of the National Research Council of Canada (NRCC) conducted an extensive wind pressure measurement on a tall building model in a boundary layer wind tunnel (5). A brief description of the method used for the pressure measurement is given below.

Wind Pressure Distribution on Building Envelope

Wind pressure measurements were made on the walls of a tall building model in an urban boundary layer which was produced in a 1.8 m by 2.7 m wind tunnel. The boundary layer was produced using an array of 1.2 m high spires across the entrance to the working section followed by 8 rows of 0.3 m cubes at 0.3 m centers. The depth of the boundary layer was about 1.14 m which indicated a correct model scale of 1/400 to achieve a full-scale urban boundary layer of 457 m characterized by the measured velocity profile

$$V_z = K\, z^{0.43} \tag{2}$$

where

V_z = wind velocity at height z above ground

K = constant

Accordingly, the building model which had plan dimensions of 7.6 cm by 11.4 cm (width/length = 1/1.5) was built to a scale of 1/400 to fit the modeled atmospheric flow scaling. It was made up of two 3.8 cm and two 7.6 cm modules, so that four building heights (22.9, 15.2, 7.6, and 3.8 cm) were achieved using different module combinations as shown in Fig. 1. The pressure taps were drilled normal to the surface on all four walls of each module. The holes, as shown in Fig. 1, were positioned in identical vertical rows but the number of horizontal rows varied between modules, so that measurements could be concentrated in regions where the pressure variation was large.

The model building was mounted at the center of a turntable and it was surrounded by a number of 3.8 cm high blocks of the same plan dimensions as the model building to simulate the high density urban area. The distance between two adjacent blocks was about 7.6 cm which represented a 30 m wide road allowance in actual condition. The majority of these blocks turned with the building model.

Wind pressure measurements were taken at the following wind angles measured counterclockwise from the normal to Side 1: 0, 5, 10, 15, 30, 45, 60, 75, and 90 deg. The pressures of each row were averaged using a weighting factor that was calculated on the basis of the area surrounding each tap. The results were expressed in terms of a weighted mean pressure coefficient at height z, C_{pz},

$$C_{pz} = \frac{2P_z}{\rho V_t^2} \qquad (3)$$

where

P_z = weighted mean pressure at height z relative to static pressure at roof level (static pressure at roof level was measured in the free stream)

ρ = air density

V_t = mean wind spead at roof level

For convenience, the mean wind speed at the roof level was converted to that measured 10 m above ground at a meteorological station by the following equation (1)

$$V_t = 0.115\ H^{0.43}\ V_s \qquad (4)$$

where

V_s = mean wind speed measured at a meteorological station, m/s

H = building height, m

In deriving Eq 4, it was assumed that the gradient heights over the two sites were 275 m for the meteorological station (6) and 457 m for the urban area. Finally, substituting Eq 4 in Eq 3 and assuming a value of 1.2 kg/m^3 for air density, one obtains

$$C_{pz} = \frac{126\ P_z}{H^{0.86}\ V_s^2} \qquad (5)$$

P_z is in pascals, H is in metres, and V_s is in metres per second.

The mean pressure coefficients so obtained are given in Fig. 2(a), (b) and 3(a), (b).

CALCULATION OF AIR INFILTRATION RATES

Under steady-state conditions, air inflows and outflows are equal for a compartment such as a non-partitioned floor space or a vertical shaft. On this basis, a set of mass flow balance equations, one for each compartment, can be set up for a building model. These equations together with Eq 1 and the measured leakage coefficients can be used to solve for the air leakage rates for the compartment under a given wind and temperature condition. The computer program for solving these equations is described in detail in Ref 7. The building model used in this study (Fig. 4) was identical to that in Ref 1. It represented an open-floor office building having plan dimensions of 45 m by 30 m. The compartments are floor spaces and a vertical shaft. The major separations are exterior walls, walls of vertical shaft and floors. The leakage coefficients of the major separations (Fig. 4), were calculated from the data given in Table 1.

Calculations of air leakage rates were made for buildings of 5, 10, 20, 30, and 40 stories under various combinations of wind speed, wind direction and stack action. The effect on air infiltration due to surrounding lower structures of uniform height was investigated for wind angles of 0, 30 and 45 deg.

Air Infiltration Due to Wind

For a wind approaching at 0 deg., Fig. 5 shows the variation of air infiltration rates per unit area of the long wall (Side 1) with wind speeds and building heights. The values of α_w are given in Table 1 for different classifications of wall air tightness. The wind speed shown in Fig. 5 is the mean wind speed measured 10 m above ground at a meteorological station.

Equations for Calculating Air Infiltration Caused by Wind

For detailed computations, it is desirable to estimate air infiltration rate using single equations. Air leakage rate caused by wind can be calculated from Eq 1 if the pressure differences across exterior walls are known. Although the pressure difference across an exterior wall varies with height, a uniform equivalent pressure difference for the whole wall can be estimated from the total air infiltration rates given in Fig. 5 by using Eq 1. This uniform equivalent pressure difference was shown to be related to wind speed and building height by the following equation (1)

$$(C_{dp})_i = \frac{126(\Delta P_e)_i}{H^{0.86} V_s^2} \qquad (6)$$

where

$(C_{dp})_i$ = uniform equivalent pressure difference coefficient

$(\Delta P_e)_i$ = uniform equivalent pressure difference across the ith wall, Pa

The maximum uniform equivalent pressure difference coefficient for all building heights was 0.75; it was found at the windward wall when the wind approached at 0 deg. With this value as a common denominator, the values of C_{dp} for the four exterior walls were non-dimensionalized and the results were plotted against wind angle in Fig. 6. The non-dimensionalized C_{dp} can also be estimated from the following equations obtained by curve fitting

$$\beta_{\theta 1} = \frac{(C_{dp})_{\theta 1}}{(C_{dp})_{01}} = \frac{(\Delta P_e)_{\theta 1}}{(\Delta P_e)_{01}} = \begin{cases} -\ 0.012\theta + 1 & \text{for } 0 \le \theta \le 45 \\ -\ 0.016\theta + 1.2 & 45 \le \theta \le 90 \end{cases}$$

$$\beta_{\theta 2} = \frac{(C_{dp})_{\theta 2}}{(C_{dp})_{01}} = \frac{(\Delta P_e)_{\theta 2}}{(\Delta P_e)_{01}} = \begin{cases} 0.018\theta - 0.44 & 0 \le \theta \le 45 \\ 0.013\theta - 0.17 & 45 \le \theta \le 90 \end{cases}$$

$$(7)$$

$$\beta_{\theta 3} = \frac{(C_{dp})_{\theta 3}}{(C_{dp})_{01}} = \frac{(\Delta P_e)_{\theta 3}}{(\Delta P_e)_{01}} = \begin{cases} -\ 0.008\theta - 0.1 & 0 \le \theta \le 45 \\ 0.002\theta - 0.55 & 45 \le \theta \le 90 \end{cases}$$

$$\beta_{\theta 4} = \frac{(C_{dp})_{\theta 4}}{(C_{dp})_{01}} = \frac{(\Delta P_e)_{\theta 4}}{(\Delta P_e)_{01}} = \begin{cases} 0.001\theta - 0.44 & 0 \le \theta \le 45 \\ 0.012\theta - 0.93 & 45 \le \theta \le 90 \end{cases}$$

Substituting Eq 6 in Eq 1 and noting that $(C_{dp})_{01} = 0.75$, one obtains

$$Q_{wo} = 0.036\ C_w\ A_1\ H^{0.56}\ V_s^{1.3} \tag{8}$$

where

C_w = leakage coefficient for exterior walls per unit wall area, $m^3/s{\cdot}m^2{\cdot}Pa^{0.65}$

Q_{wo} = air infiltration due to wind at 0 deg., m^3/s

A_1 = area of long wall (Side 1), m^2

Likewise, substituting Eq 6 and Eq 7 in Eq 1, one obtains

$$Q_{w\theta} = 0.036\ C_w\ H^{0.56}\ V_s^{1.3}\ \sum_i jA_i\ \beta_{\theta i}^{0.65} \tag{9}$$

where

$Q_{w\theta}$ = air infiltration due to wind at θ, m^3/s

A_i = area of wall i; i = 1, 2, 3, 4

j = 1 or 0 if $\beta_{\theta i} > 0$ or $\beta_{\theta i} < 0$

Finally, dividing Eq 9 by Eq 8 one has the correction factor, α_θ, for wind direction

$$\alpha_\theta = \frac{Q_{w\theta}}{Q_{wo}} = \beta_{\theta 1}^{0.65} + \frac{w}{\ell}\ \beta_{\theta 2}^{0.65} \tag{10}$$

α_θ is plotted in Fig. 7 for various wind directions.

Nearby structures can affect the wind-induced air flow pattern around a building and hence the air infiltration rates. At present, physical modeling seems to be the only practical method for determination of air flow pattern for a building downstream of other structures. However, due to the great variety of building sites, a systematic study of the problem of shielding is not feasible. In order to provide data for general design purposes, an ideal building site, a tall building surrounded by lower structures of uniform height, was considered. Thus, calculations of air leakage rates were made using the measured wind pressure data corresponding to various height ratios of the adjacent structures to the building, h/H. The results (Fig. 8) indicate that, regardless of wind direction, the ratio of air infiltration rates for a given h/H to that for h/H = 1/6 decreases exponentially as the value of h/H increases. Based on the results, an equation for estimating the correction factor of shielding was obtained by curve fitting

$$\alpha_{sh} = \frac{(Q_w)_{h/H}}{(Q_w)_{1/6}} = 1.15\ \exp\ (-0.85\ h/H) \tag{11}$$

where

α_{sh} = correction factor of shielding

Q_w = air infiltration rate due to wind

h = average height of adjacent structures

H = height of building

It should be pointed out that α_{sh} is not valid for the case of a building partially protected by an adjacent tall building.

Air Infiltration Caused by Combined Wind and Stack Action

Fig. 9(a) and 9(b) show the relationship between Q_{ws}/Q_{lrg} and Q_{sml}/Q_{lrg} where Q_{sml} or Q_{lrg} is the smaller or larger value, respectively, of air infiltration due to wind or stack action, and Q_{ws} is that due to the combined action of the two forces. The relationship can also be approximately expressed by the following equations:

$$\alpha_{ws} = \frac{Q_{ws}}{Q_{lrg}} = \begin{cases} (-0.0074\theta + 0.39)\left(\dfrac{Q_{sml}}{Q_{lrg}}\right)^{3.6} + 1 & \text{for} \quad 0 \leq \theta \leq 45 \\ (0.01\theta - 0.48)\left(\dfrac{Q_{sml}}{Q_{lrg}}\right)^{2.5} + 1 & \quad 45 < \theta \leq 90 \end{cases} \tag{12}$$

To apply Eq 12 it is necessary to know the air infiltration rate due to stack action, Q_s. For tall buildings, the equation for estimating Q_s as given in Ref 1 takes the form

$$Q_s = 0.96\ C_w\ S\ (\Delta T/T_o)^{0.65}\ H^{1.65} \tag{13}$$

where S is the building perimeter in metres, ΔT is the inside-outside temperature difference in kelvins and T_o is the outside air temperature in kelvins.

Summary of Procedure of Air Infiltration Calculation

The suggested method for calculating air infiltration for a tall building surrounded by lower structures of uniform height can be summarized as follows:

1. Calculate air infiltration rate caused by stack action, using Eq 13

$$Q_s = 0.96\ C_w\ S\ \left(\frac{\Delta T}{T_o}\right)^{0.65}\ H^{1.65} \tag{13}$$

2. Estimate air infiltration caused by wind, using the following equation obtained by combining Eq 9 and Eq 11, or using Fig. 5, 7 and 8:

$$Q_w = 0.036\ C_w\ H^{0.56}\ V_s^{1.3}\ \alpha_{sh} \sum_i jA_i\ \beta_{\theta i}^{0.65} \tag{14}$$

3. Determine Q_{sml} and Q_{lrg} from the calculated Q_s and Q_w and, from Eq 12, calculate air infiltration caused by the combined wind and stack action, or use Fig. 9(a) and 9(b)

$$Q_{ws} = \alpha_{ws}\ Q_{lrg} \tag{12}$$

In the above equations, C_w is given in Table 1; $\beta_{\theta i}$ and α_{sh} can be calculated from Eq 7 and Eq 11.

DISCUSSION

The proposed method for calculating air infiltration rate is strictly valid only for a tall building surrounded by lower structures of uniform height because of the wind pressure coefficients used. It may not be generalized to apply for a tall building partially protected by another tall building unless they are sufficiently far apart. Based on the measurements made by Bailey and Vincent (8), the minimum distance for which the effect of an adjacent tall building may be neglected is estimated to be about 8 building widths.

Fig. 2(a), (b) and 3(a), (b) indicate that the mean pressure coefficient on the windward wall decreases as the wind angle deviates from the normal to that wall and as the height of adjacent structures increases. The height of adjacent structures used to obtain C_{pz} was 3.8 cm which represented a 5-story building in full scale. This height was chosen because it was approximately equal to the average building height in a large city such as Toronto.

Fig. 6 shows that for a long wall (Side 1), $(C_{dp})_1$ is maximum at $\theta = 0$ deg. and it decreases continuously to zero as θ increases to 75 deg. For a short wall (Side 2), $(C_{dp})_2$ is zero at 25 deg. and it increases continuously with θ to a maximum value at 90 deg. Thus, as the wind angle, θ, changes from 0 to 90 deg., air will infiltrate a building through Side 1 for $\theta<25$ deg., and through both Sides 1 and 2 for θ varying from 25 to 75 deg., and finally through Side 2 for $75<\theta\leq 90$ deg. Similar results were observed for a fully exposed tall building in the suburb (1).

Fig. 9(a) and 9(b) indicate that if Q_s is equal to Q_w, the resultant air infiltration is about 40%, 17% and 6% higher than Q_s or Q_w for wind angles of 0 (Or 90), 30 (or 60) and 45 deg. respectively. Thus, the results appear to suggest that one effective way to cut down heat loss due to infiltration for buildings under design is to orient them away from the winter prevailing wind direction.

The factor α_{sh} for estimating Q_w was derived for h/H = 1/6. To investigate the applicability of this factor to other shielding conditions, Fig. 10 shows the relationship between $(Q_{ws}/Q_{lrg} - 1)$ and Q_{sml}/Q_{lrg} for various values of h/H and wind angles. It is evident that α_{sh} is a weak function of h/H especially when the wind direction is not perpendicular to the wall. Thus, the factor α_{sh} can also be used to estimate Q_{ws} under the shielding condition considered.

The predicted air infiltration rates using the suggested method was compared with those based on the computer building model under various conditions. As shown in Fig. 11, the agreement between the two results is within 5%.

CONCLUSIONS

A method was presented for predicting air infiltration rate for a tall building (w/l = 1/1.5) surrounded by lower structures of uniform height under various combinations of wind speeds, wind angles, and air temperature. The method may be generalized to apply for a tall building in an urban area if the building is about 8 building widths away from other tall buildings. The predicted air infiltration rates are shown to be accurate within 5% compared with those based on the computer building model.

Air infiltration caused by wind was found to be a strong function of wind direction. The results indicated that the maximum air infiltration was produced by a wind that approached at 0 deg. and the minimum air infiltration occurred at 75 deg. wind angle.

Air infiltration caused by the combination of wind and stack action is dependent on the magnitude of each and the wind direction. If the air infiltration rates caused by wind or stack action acting separately are equal, the air infiltration rate caused by the combined action is higher than that due to each action by about 40% for wind angles of 0 or 90 deg. and 6% for 45 deg.

NOMENCLATURE

A_1 = area of long wall (Side 1), m^2

A_i = area of wall i, m^2; i = 1, 2, 3, 4

C_j = leakage coefficient of building component; see Table 1

C_w = leakage coefficient for exterior walls per unit wall area, $m^3/s \cdot m^2 \cdot Pa^{0.65}$

C_{pz} = weighted mean pressure coefficient; see Eq 3

$(C_{dp})_i$ = uniform equivalent pressure difference coefficient of wall i, i = 1, 2, 3, 4; see Eq 6

h = average height of adjacent structures, m

H = building height, m

K = constant

ΔP_j = pressure difference across an opening, Pa

$(\Delta P_e)_i$ = uniform equivalent pressure difference across ith wall, Pa; i = 1, 2, 3, 4

P_z = weighted mean pressure at height z relative to static pressure at roof level, Pa

Q_s = air infiltration rate caused by stack action, m^3/s

Q_w = air infiltration rate caused by wind, m^3/s

$Q_{w\theta}$ = air infiltration rate caused by wind at θ, m^3/s

Q_{wo} = air infiltration rate caused by wind at 0 deg., m^3/s

Q_{ws} = air infiltration rate caused by combined wind and stack action, m^3/s

Q_{lrg} = larger value of Q_w and Q_s, m^3/s

Q_{sml} = smaller value of Q_w and Q_s, m^3/s

S = perimeter of the building, m

T_o = outside air temperature, K

ΔT = inside-outside temperature difference, K

V_s = mean wind speed measured at a meteorological station, m/s

V_t = mean wind speed at roof level, m/s

V_z = mean wind speed at height z above ground, m/s

$\alpha_\theta = \frac{Q_{w\theta}}{Q_{wo}}$ = correction factor for wind direction

$\alpha_{sh} = \frac{(Q_w)_{h/H}}{(Q_w)_{1/6}}$ = correction factor for shielding

$\alpha_{ws} = \frac{Q_{ws}}{Q_{lrg}}$ = correction factor for combined wind and stack action

$\beta_{\theta i} = \frac{(C_{dp})_{\theta i}}{(C_{dp})_{01}}$

ρ = air density

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ACKNOWLEDGEMENT

The author gratefully acknowledges the contribution of D.G. Stephenson, G.T. Tamura and A. Konrad in the preparation of this paper. This paper is a contribution from the Division of Building Research, National Research Council of Canada and is published with the approval of the Director of the Division.

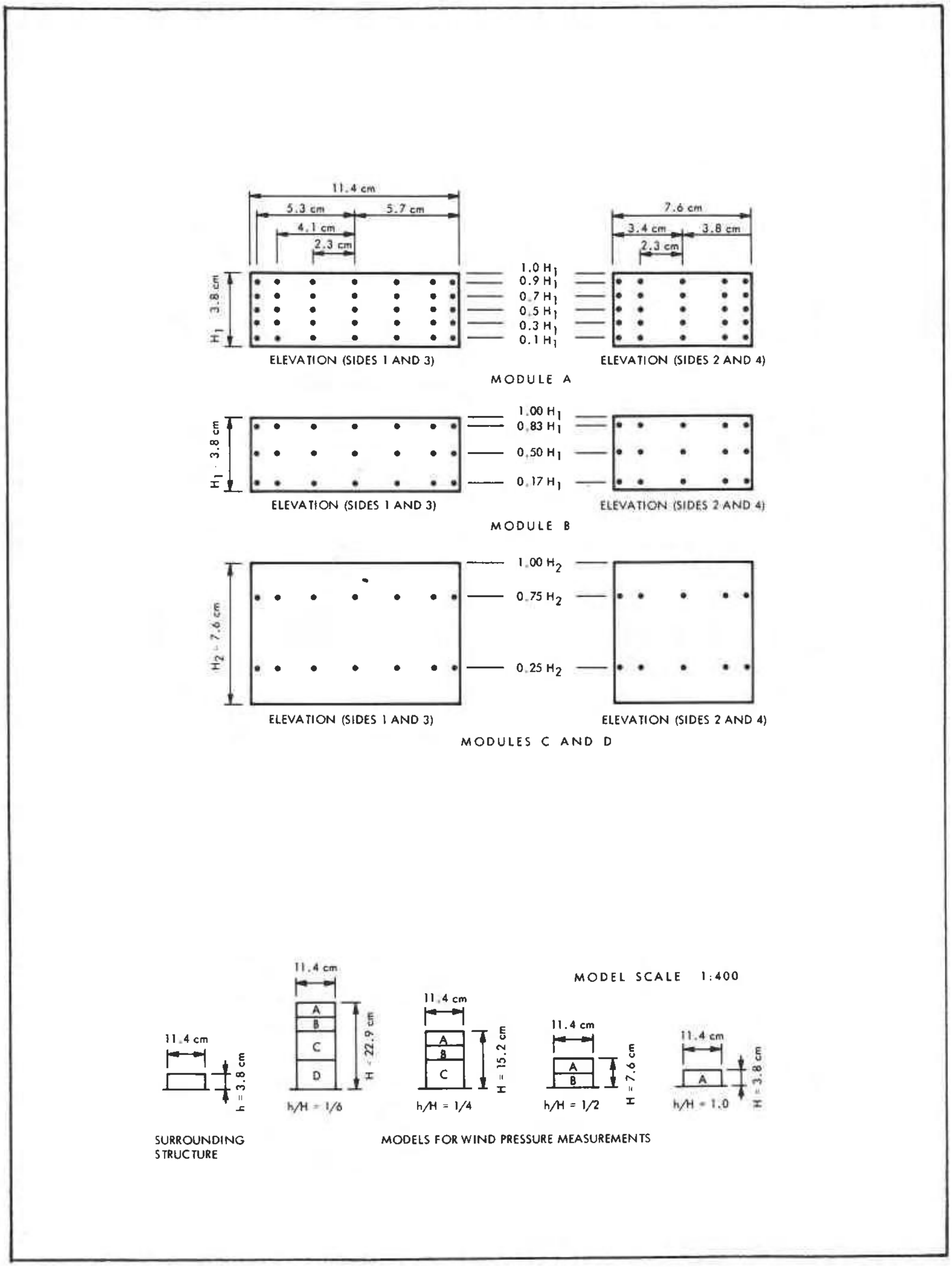

Fig. 1 Dimensions of building models and positions of pressure taps

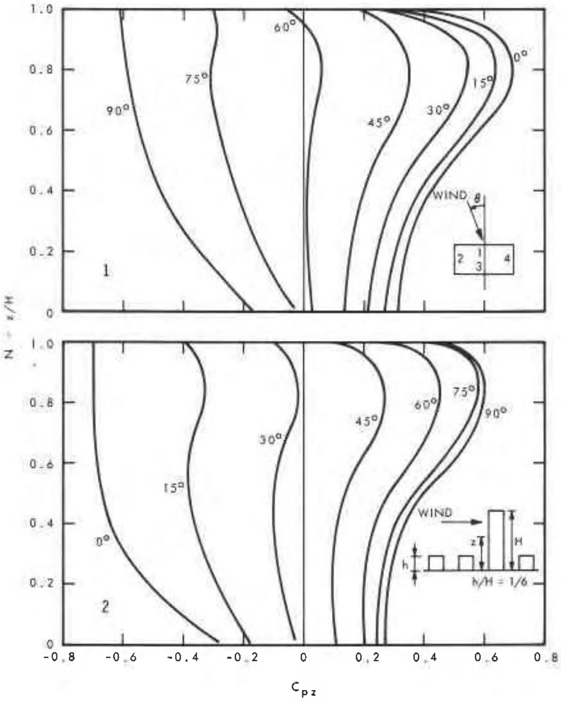

Fig. 2a Vertical distribution of mean wind pressure coefficients of sides 1 and 2 for h/H = 1/6

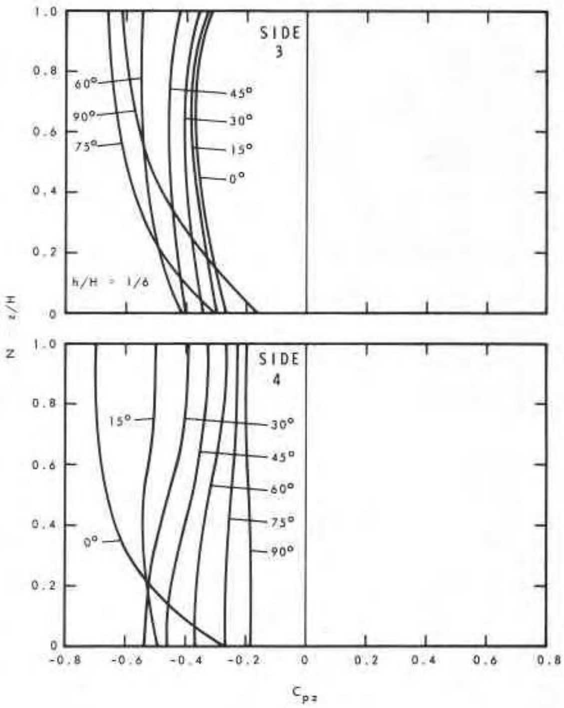

Fig. 2b Vertical distribution of mean wind pressure coefficients of sides 3 and 4 for h/H = 1/6

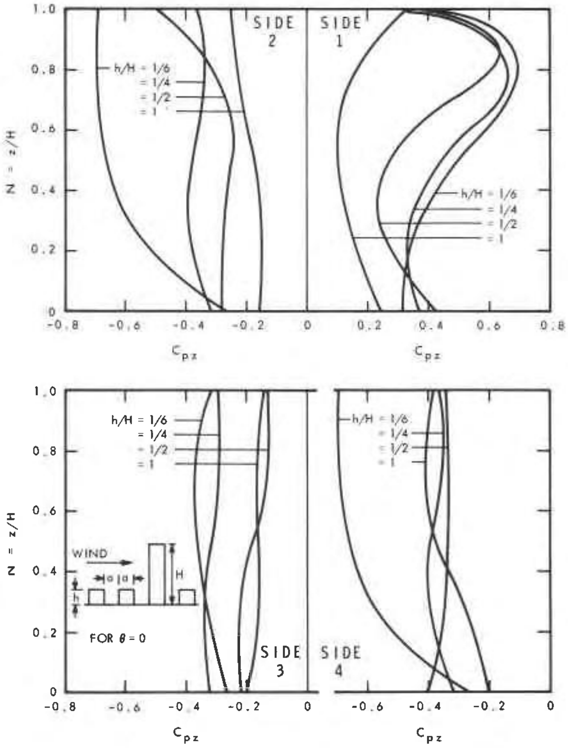

Fig. 3a Vertical distribution of mean wind pressure coefficients for Θ = 0° and various values of h/H

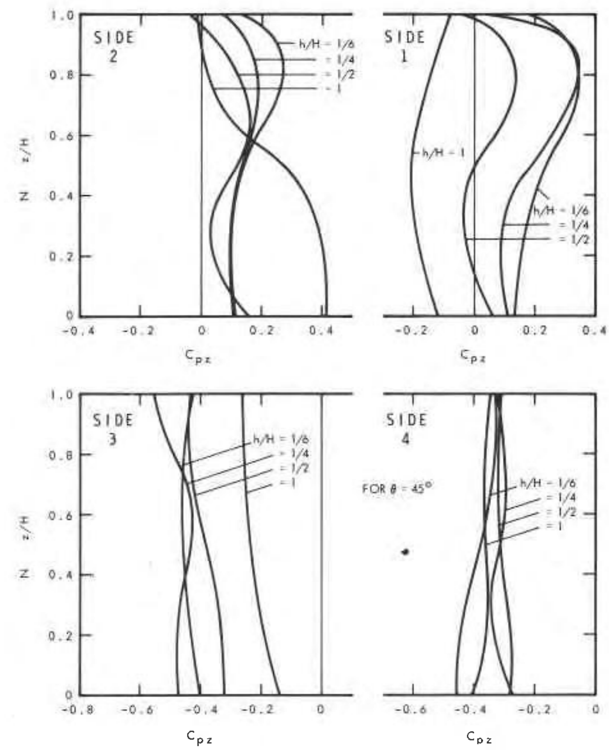

Fig. 3b Vertical distribution of mean wind pressure coefficients for Θ = 45° and various values of h/H

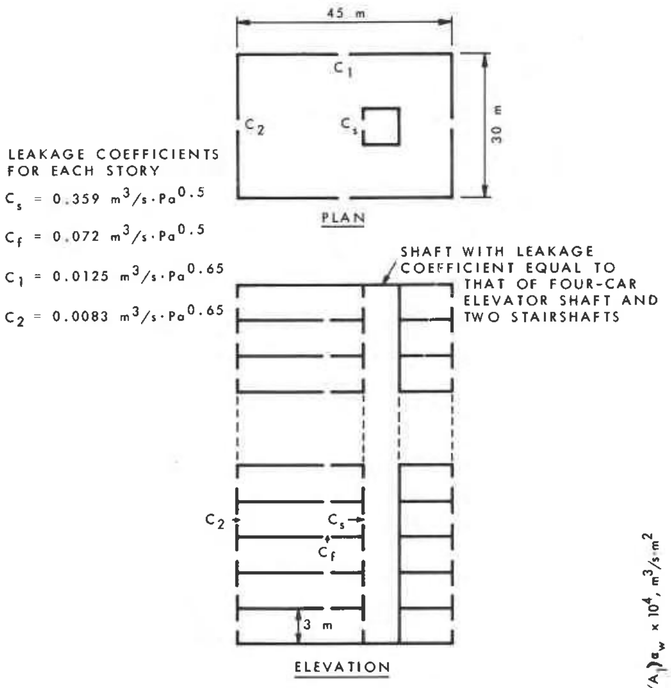

Fig. 4 Computer building model

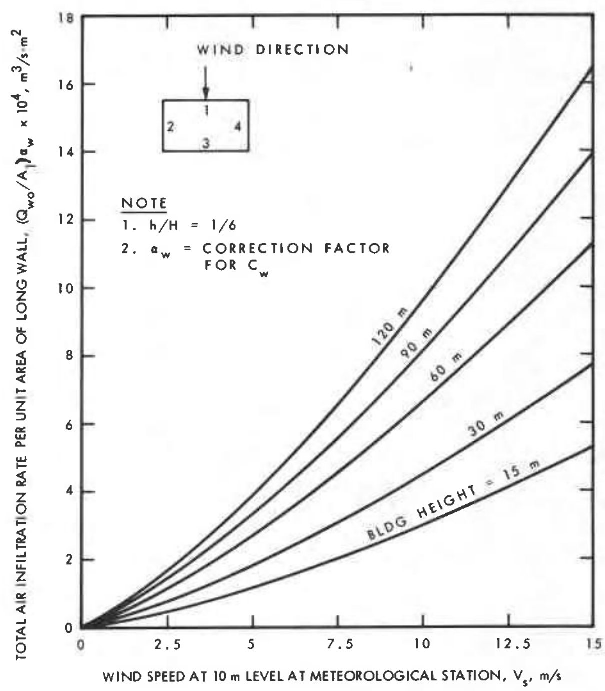

Fig. 5 Air infiltration rates caused by wind for a tall building surrounded by lower structures of uniform height

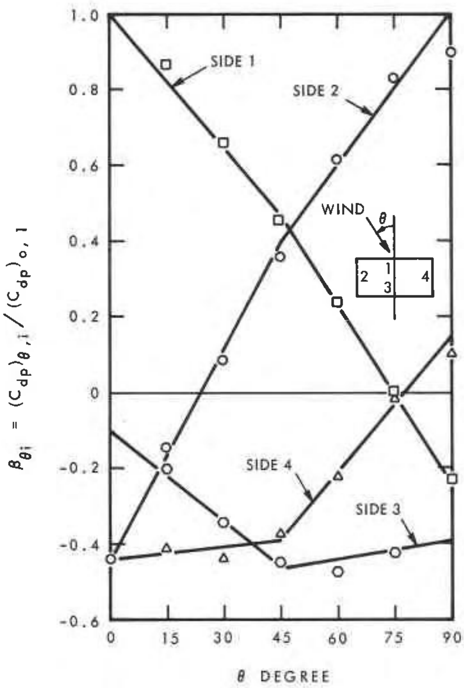

Fig. 6 Relationship between normalized uniform equivalent pressure difference coefficient and wind direction

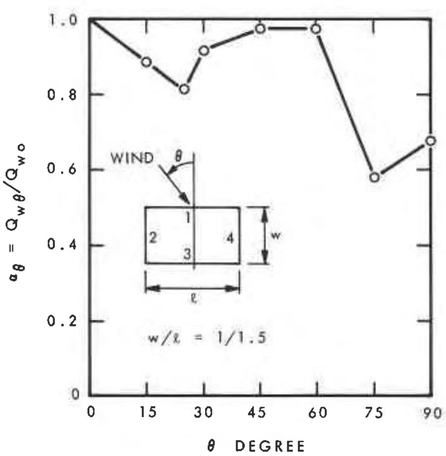

Fig. 7 Factor for determining air infiltration rate for various wind angles

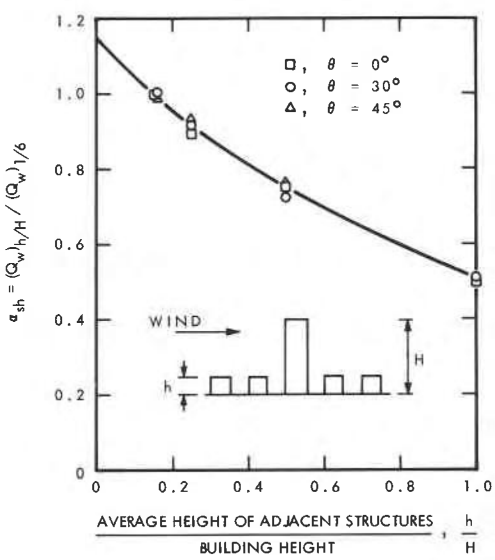

Fig. 8 Relationship between air infiltration rates due to wind and average height of adjacent structures

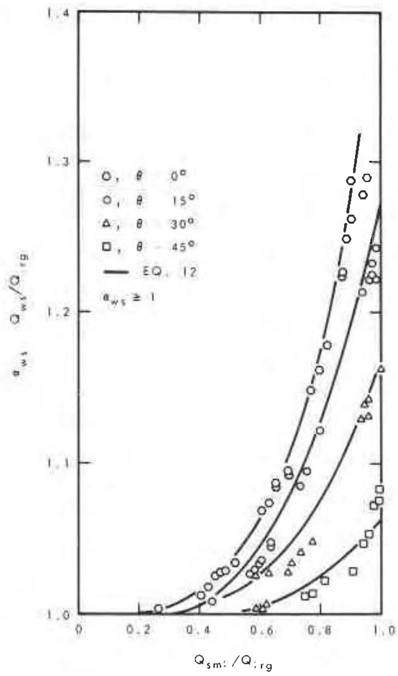

Fig. 9a Factor for determining air infiltration rates due to combined action of wind and stack action for $0^{o} \leq \theta \leq 45^{o}$

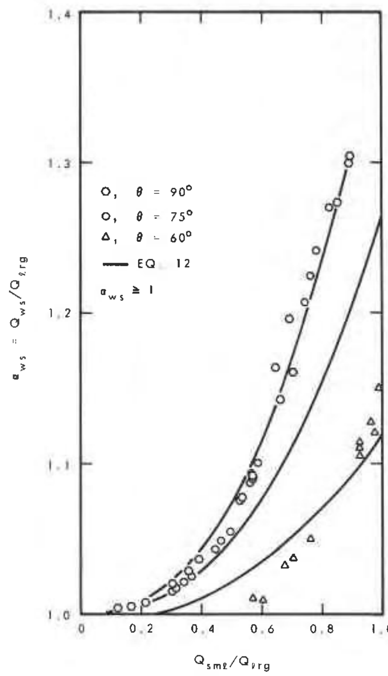

Fig. 9b Factor for determining air infiltration rates due to combined action of wind and stack action for $45^{o} < \theta \leq 90^{o}$

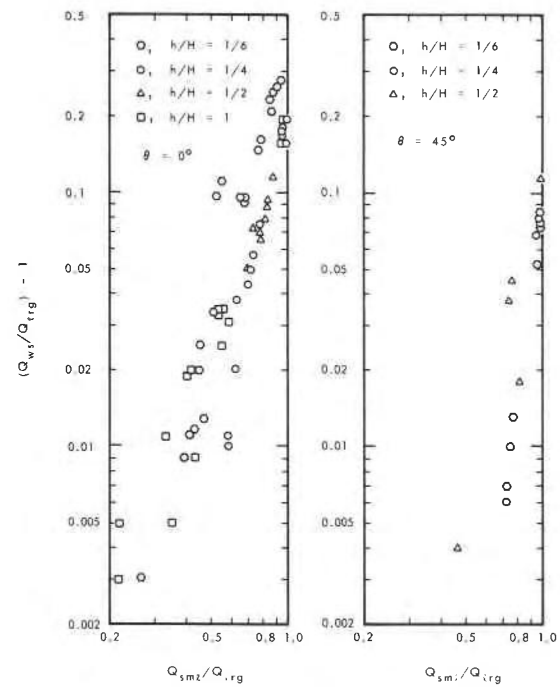

Fig. 10 Effect of adjacent structures on factors for determining air infiltration rates due to combined action of wind and stack action

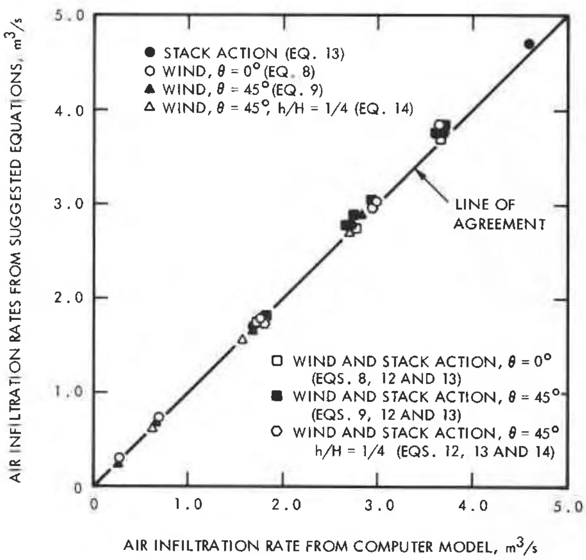

Fig. 11 Comparison of calculated air infiltration rates with that obtained using computer building model