#3362

No. 3127

CORRELATIONS FOR PRESSURE DISTRIBUTION ON BUILDINGS AND CALCULATION OF NATURAL-VENTILATION AIRFLOW

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ABSTRACT

A review of the worldwide data base on distribution of pressure coefficients (C_p) on building surfaces yielded usable data from eight different investigators for low-rise buildings and one source for high-rise buildings. It was found that average surface pressure coefficients for low rise buildings were adequate, and local data were assimilated as 544 average surface C_p. A nonlinear regression with wind incidence angle and building side ratio as variables was found to predict these data with a correlation coefficient of 0.80. Local pressure coefficients rather than average surface C_p were used for high rise buildings. More than 5,000 data points were fitted with another nonlinear regression involving the earlier variables plus the location coordinates.

Building pressure coefficient correlations developed in this paper can be useful for infiltration and indoor air quality studies as well as for natural ventilation airflow calculations.

A structured procedure for calculating wind-driven natural ventilation rates is given in appendix A. This procedure is an enhanced version of the Vickery (1983) algorithm for calculating airflow through buildings.

INTRODUCTION

Better knowledge of pressure distributions on building surfaces has become more importance in recent years for several reasons. The need to maintain indoor air quality by providing minimum air changes in buildings requires knowledge of surface pressure distribution in order to calculate infiltration air flows through buildings. As the costs of mechanical cooling have steadily increased, interest in passive cooling strategies such as natural ventilation has also increased. Detailed knowledge of pressure distribution is also necessary for the calculation of natural ventilation. Parameters such as building geometry, terrain, and other factors influence the value of pressure coefficient (C_p).

Over the years, the civil engineering community has conducted wind tunnel investigations of C_p distributions to determine their importance in wind load calculations. This paper attempts to assimilate this worldwide data base for use in natural ventilation calculations. Results of this ASHRAE-sponsored study have produced a significant advance in the state of the

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art (ASHRAE 1985). However, the correlations are far from complete, since data are available only for rectangular buildings --quite different from typical residential floor plans.

The range of low- and high-rise building geometries curve fitted is:

Low rise: Floor Plan - rectangular
- 1 <= long to short wall ratio <= 8
- 0.1 <= eave height to short wall ratio <= 0.4 (typical of 1 to 2 story)
- 0 <= overhang/eave height <= 0.2
- 0 <= roof angle <= 60 degrees

High rise: Floor Plan - rectangular
- 1 <= long to short wall ratio <= 4
- 1 <= eave height to short wall ratio <= 8
- overhang = none
- roof angle = 0

The worldwide data base on pressure coefficient (C_p - defined in Appendix, Section A.1) distribution on building surfaces was reviewed, providing data from eight different investigators for low-rise buildings and one source for high-rise buildings. It was found that average surface pressure coefficients for low-rise buildings were adequate, and local data were assimilated as 544 average surface C_p. A nonlinear regression with wind incidence angle and building side ratio as variables was found to predict these data with a correlation coefficient of 0.80.

Local pressure coefficients, rather than surface average, were used for high-rise buildings. More than 5,000 data points were fitted with another nonlinear regression involving the earlier variables plus the location coordinates. Building pressure coefficient correlations developed in this work can be useful for infiltration and indoor air quality studies as well as for natural ventilation airflow calculations.

A structured procedure for calculating wind driven natural ventilation rates is given in appendix A. This procedure is an enhanced version of the Vickery (1983) algorithm for calculating airflows in buildings.

APPROACH TO DATA REDUCTION

The coefficient of pressure over a building surface varies with the position on the surface, particularly near the edges. However, such data are extremely voluminous and primarily important for wind load calculations. A logical simplification is to use the average surface C_p for calculating ventilation rates for low-rise buildings. Swami and Chandra (1987) found that the error introduced by using average surface C_p rather than local C_p was generally about 5%. A similar comparison by Wiren (1985) showed the error to be under 10%. However, C_p variations along the height of high-rise buildings can be relatively large. Thus, the regression equations for high-rise buildings were developed for local rather than average surface C_p.

Wind Angle and Building Geometry

The coefficient of pressure varies considerably with the approach wind angle and, to a lesser extent, with the geometry of the building (i.e., side ratio and roof slopes).

C_p data, either mean or local, are usually given in terms of the wind angle for each of the four surfaces constituting the house. Most researchers have defined the wind angle with respect to the windward wall of the building, and C_p data for all four walls are tabulated with respect to the wind angle. The disadvantage of this approach is having to carry the wall number as an additional parameter for curve fitting. It was felt that defining the wind angle with respect to the actual surface for which C_p is sought, rather than any one surface, would be more appropriate and would be less cumbersome for curve fitting. Since all data are available for rectangular buildings, the data could easily be converted in terms of our wind angle definition. This would eliminate wall number as a dependent parameter. The wind angle is defined to be the angle between the outward normal of a surface and the wind direction and is always a positive value between 0 and 180 degrees (see Figure 1). Due to the symmetry of the data, the actual sign of the angle is unimportant. The solid line in the figure is the wall surface under consideration, and the dotted line indicates the rest of the building. To account for the effect of the adjacent wall, the parameter side ratio (S, in Figure 1) is defined and is another parameter influencing the C_p value. Data for all the surfaces were converted into this form. Samples of such a conversion are provided in Swami and Chandra (1987).

Two other parameters affecting C_p are the roof slope (γ) of the wall under consideration and the roof slope (δ) of the adjacent wall (illustrated in Figure 2).

Normalized C_p (NC_p)

Different researchers have referenced C_p based on velocities at different heights. Since it is proposed to use C_p referenced to the velocity at the building height, all C_p data in the literature must be re-referenced. To do this, the velocity profile of the study will have to be known a priori. This effort can be considerably simplified if C_p at different wind angles are normalized with respect to C_p at a fixed wind angle. Since C_p at a wind angle of zero degrees is usually most reliable and this value is provided by most studies, all C_p are normalized with respect to the C_p at the wind angle of zero degrees. The normalized values thus become independent of the reference height, and it is only needed to reference the C_p at zero degrees to the building height. This will result in the value of normalized C_p at zero degrees to be 1.0 regardless of all other parameters, which facilitates in curve fitting.

CONSOLIDATION OF AVAILABLE C_p DATA

Pressure coefficients from a number of sources were examined for useful data for data reduction and consolidation. The Air Infiltration Centre bibliography (Allen 1984) was used extensively to search for original source documents. In addition, some researchers in the field were contacted directly. Table 1 summarizes the sources used and gives the parameters utilized by the authors and the C_p values at zero incidence. Refer to Swami and Chandra (1987) for the details of data extraction.

The data extracted for low rise buildings yielded 544 average wall data points representing several thousand local C_p data that were digitized from contour plots.

A computer program was used to obtain curve fit for the normalized C_p data by step-wise regression techniques. The program was run with a large number of possible parameters, generated from the combination of wind angle (α), side ratio (S), and roof angles (γ and δ). Wind angle and building side ratio were found to significantly influence C_p, while roof angles were insignificant. This could be due to some conflicting data as well as to the fact that only wall C_p distributions are being correlated.

With the significant parameters obtained, the actual form was chosen. The nature of the data imposed several constraints.

1. Regardless of all other parameters, the normalized C_p must always be equal to 1.0 for zero degrees wind angle.

2. The terms containing the roof angles in the equation must disappear from the equation when they are zero, leaving the rest of the equation intact.

3. Since the natural logarithm of the side ratio is the significant parameter, this term will become zero for S=1. These terms must be chosen so that they do not affect the other terms of the equation. To abide by these constraints, terms containing side ratio as well as roof angles were combined with sine functions of wind angle so that these terms would vanish for wind angle of zero degrees. The final recommended equation is:

$$NC_p = Ln(C0 + C1*SIN(\alpha/2) + C2*SIN^2(\alpha) + C3*SIN^3(2*\alpha*G) + C4*COS(\alpha/2) + C5*G^2*SIN^2(\alpha/2) + C6*COS^2(\alpha/2)) \quad (1)$$

where:

NCp is the normalized Cp
Ln denotes the natural logarithm
α is the wind angle in degrees
G = Ln(S) (natural log of the side ratio S)

The coefficients of the equation are:

C0 = 1.248	C1 = -0.703	C2 = -1.175	C3 = 0.131
C4 = 0.769	C5 = 0.07	C6 = 0.717	

(2)

The correlation coefficient for the above equation is 0.797, which is a good value considering the diversity of the data. Figure 3 shows a scatter plot of the observed versus predicted data for low-rise buildings based on Equation 1. Longer correlations involving more terms, including roof angle terms, and a slightly higher correlation coefficient of 0.811 may be found in Swami and Chandra (1987).

The observed NC_p and that calculated using Equation 1 are plotted against wind angle for two cases in Figures 4 and 5. Note that the curve fit performs adequately compared to the experimental data. Similar comparisons for all low-rise building data are given in Swami and Chandra (1987).

C_p at Zero Incidence

Table 1 gives C_p values at zero incidence from each source for the long wall and short wall (see definition of long wall and short wall in Appendix A.1). The data are highly diverse, showing no firm trend with respect to any parameter. While it is expected that the open terrain should have higher C_p than the suburban terrain -- which is the case with Vickery's (1983) data -- cross comparison of Vickery's (1983) open terrain data with suburban data of other references such as Ashley (1984) shows just the opposite. Jensen's (1965) values for large turbulence are always higher than for small turbulence, indicating a conflict in the data trend. On the other hand, Akins (1979) shows no change between short and long wall for all three aspect ratios. It should be pointed out that the idea of normalized C_p developed earlier removes many of the uncertainties of individual experiments from which data are gathered.

In light of the above, it is suggested that a uniform value of 0.60 be chosen to represent C_p at zero incidence for all types of low rise buildings. This represents the average of all C_ps at zero incidence.

EFFECT OF SURROUNDING BUILDINGS

Surrounding buildings can have significant effects on the airflow through buildings. Correlations for change in C_p due to the presence of three specific surrounding patterns-- rectangular, hexagonal, and a single neighboring building -- were carried out by Swami and Chandra (1987) from the data available in Wiren (1985). Since these are only specific effects, they are not presented here. However, correction factors were developed based on the generalized shielding coefficients of Sherman and Grimsrud (1982), and the effects of wingwalls, garages, and U shaped floor plans are presented below. They are believed to be of more practical significance.

Correction for Shielding Effects

The factors for reduction in airflow due to shielding were calculated based on the generalized shielding coefficients of Sherman and Grimsrud (1982). Taking their Shielding Class I to represent a totally unobstructed house, the correction factor to be applied for the other classes was calculated by taking the ratio of the Sherman and Grimsrud coefficients with respect to the unshielded class. The calculated correction factors are given in Table 2. Note that the correction factors given in the table should be applied to the ventilation flow rate and not C_p.

$$\text{Corrected ACH} = \text{ACH} * \text{SCF} \quad (3)$$

where

ACH - air changes per hour

SCF - shielding correction factor

Presence of Garage or Wing Walls

The presence of a garage wall or wingwall protruding from a wall will drastically affect the value of C_p depending on the approach wind angle (Figure 6 shows a typical layout). Since no measured data are available for this case of practical importance, the following is our best engineering judgement. Studies done by Chandra et al. (1983) show that for an angle of up to 90 degrees between the garage wall and the approach wind (as shown in the figure), the value of C_p on the wall may be assumed to be the value at zero incidence. For angles in the positive direction beyond 90 degrees, the effect of the garage or wing wall is minimal and therefore no modification is suggested. For angles in the negative direction, as shown in Figure 6, the presence of the garage or wingwall produces negative pressures as if the wind is approaching from the leeward side. In this case, it is suggested that the window areas of the wall may be added to the window areas of the leeward wall of the building.

U-Shaped Building

Figure 7 shows a typical U-shaped building. Since measured data are unavailable for this common building shape also, commonsense guidelines are recommended. The C_p of the wall forming the inner surfaces of the U should be modified as follows. For approach wind up to 45 degrees on both sides of line OO (Figure 7), the C_p values of all the U-walls may be taken as the value at zero incidence since positive pressures will be experienced by those walls. For angles beyond 45 degrees and up to 60 degrees on both sides of line OO, the wall facing away from the wind approach is likely to be experiencing suction conditions, while the other two walls are likely to be experiencing positive pressures. The wall facing away from the wind direction should be treated as if it were a leeward wall, and its aperture area should be added to the aperture area of the leeward wall of the building. The C_p for the other two walls of the U may be taken as C_p at zero incidence. For angles beyond 60 degrees, the flow is likely to bypass the U region, and all walls of the U will experience suction. Therefore, the areas of windows on these walls should be added to the window areas of the appropriate leeward wall. Figure 7 illustrates the different cases.

TERRAIN EFFECTS

Wind engineers have developed five standard terrain classifications, ranging from open ocean fronts to the center of large cities. The terrain enters into the calculation of the reference wind speed, as discussed in the appendix (Section A.2), since the terrain affects the shape of the approach wind velocity profile.

Another question on terrain effects is whether the shape of the velocity profile affects the C_p directly. Akins (1976) conducted a systematic investigation of five velocity profiles of high-rise buildings and found that C_p dependence on terrain virtually vanishes if the C_p is defined with wind velocities at local height rather than at some fixed height. No one has yet conducted a systematic study for low-rise buildings, encompassing all five terrain classes. Most available data are for terrain classes II or III (see Table A-1 for terrain classifications) and the data are conflicting. Thus, we have chosen to ignore the effect of velocity profile shape on C_p.

DATA REDUCTION FOR HIGH-RISE BUILDING

More than 5,000 data points from Akins (1976) are available for all four surfaces for three buildings (length-to-width-ratios 1, 2, and 4) and for five wind angles, as well as for 110 locations on the surface of each wall. The horizontal and vertical coordinates (XL and ZH) of the points on the wall are nondimensionalized with respect to the length and height of the wall. C_p is referenced with respect to the velocity at the height of measurement.

Because Akins (1976) in using local C_ps found no dependence on either terrain or height of the building, no attempt has been made to normalize the C_p data, and it was decided to curve fit the actual C_p data. However, the data were converted according to our conventions of wind angle (α) and side ratio (S) and x-axis origin to eliminate the wall surface number as one of the variables (see Figure 8). The final equation obtained for C_p for high-rise buildings is:

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Cp = C0 + C1*Ar + C2*COS(2*α) + C3*ZH*SIN(α)*S**0.169 + C4*COS(2*α)*S**0.279 +
     C5*SIN(2*α) + C6*ZH*COS(α) + C7*COS(Xr) + C8*COS(Xr*α) + C9*COS(Xr*α)*S**0.245 +
     C10*ZH*SIN(α) + C11*Xr*SIN(α) + C12*XL + C13*COS(Xr)*S**0.85          (4)
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where

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Ar = α*3.1415/180 (wind angle in radians)
Xr = (XL-0.5)/0.5
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and

α, S, XL and ZH have their usual meaning (See definition in Section A.1)

The coefficients of the equation are:

C0	= 0.068	C1	= -0.839	C2	= 1.733	per radian
C3	= -1.556	C4	= -0.922	C5	= 0.344	
C6	= -0.801	C7	= 1.118	C8	= -0.961	
C9	= 0.691	C10	= 2.515	C11	= 0.399	
C12	= -0.431	C13	= 0.046			(5)

Figure 9 shows a scatter plot of observed versus predicted C_p for high-rise buildings based on Equation 4.

COMPARISON OF PREDICTED AND MEASURED VENTILATION RATES

Chandra et al. (1983) provides ventilation rates measured in a photovoltaic house (FSEC·PV house) for three different wind directions. This is a typical three-bedroom, two-bath residence with photovoltaic panels. These values were compared against values predicted from the correlations obtained here and the calculation procedure shown in Appendix A. Figure 10 shows the plan of the house and Table 3 shows the comparison. In summary, we can conclude that the suggested procedure and the correlations used are quite accurate for calculating natural ventilation airflow rates. We could not find other experimental measurements of natural ventilation airflow rates for comparison.

DISCUSSIONS AND CONCLUSIONS

The objective of this study was to synthesize and develop correlations for C_p data for the widest possible range of building shapes. Thus, we had to tackle the problem of correlating conflicting data from different sources, as can be seen in Table 1, for the normal incidence C_p value $C_p(0)$. Since the major objective was to develop C_p correlations as a function of the wind incidence angle and the building geometrical parameters, the only feasible way to resolve the inconsistency in the data was to normalize the C_p data with the $C_p(0)$ value. We do recommend a $C_p(0)$ value of 0.6, which is consistent with the carefully conducted tests reported in Cermak et al. (1981) and Akins and Cermak (1979). It also happens to predict the measured ventilation rates to 11% for the only field-measured data we could locate. Thus, we feel that the proposed correlations are reasonable.

We hasten to add that calculating airflows through buildings is difficult and cannot be done with precision. Uncertainties in the estimation of site wind speed and the effect of surrounding buildings are likely to be equal to or greater than the uncertainty in estimating C_p from the proposed correlations.

The proposed procedure uses C_p data from a variety of sources. All sources give data for simple rectangular floor plans. It will probably be correct to state that over 90% of single-family detached housing in the U.S. is not constructed as a simple rectangle but is L-shaped or U-shaped or is even more complex due to the presence of garages, porches, etc. Realizing this, we have given engineering suggestions for computing average wall C_p for these popular house shapes. It must be stated again that these are estimates based on educated guesswork. Systematic wind tunnel experiments must be conducted on L, U, and other floor plans to accurately analyze these cases.

Another area where data are inadequate is in the area of roof slopes. Only a few studies have data on models with various roof slopes. In our data analysis, we found no systematic effect of roof slope, so the recommended correlation does not have roof slope as a variable. However, one study did systematically study the effect of roof slope. These data were diluted by other studies with random roof slopes, so roof slope does not appear as a statistically significant parameter. Additional research on this topic is desirable.

NOMENCLATURE

A - area, ft^2
a - terrain constant multiplier, ND (ND - nondimensional)
ACH - air change per hour, h^{-1}
b - terrain constant exponent, ND
Ca - corrected flow coefficient, ND
Cp - pressure coefficient, ND
CQ - flow coefficient, ND
h - height at which meterological wind data are available, ft
H - reference height, ft
L - longer side dimension of building, ft
NCp - normalized pressure coefficient, ND
p - local wind pressure, psf
Q - airflow rate, ft^3/s
S - side ratio, ND
SCF - shielding correction factor, ND
V - velocity, ft/s
XL - dimensionless horizontal window location coordinate, ND
ZH - dimensionless vertical window location coordinate, ND
W - smaller side dimension of buildings, ft
ZV - zone volume, ft^3

Greek

α - wind angle with respect to outward normal of a wall, degree
γ - roof angle, degree
δ - roof angle, degree
ρ - air density, lb/ft^3
Σ - summation
Δ - difference

Subscript

0 - refers to zero incidence as in Cp_0
b - building terrain
e - effective
h - value at height h
H - value at reference height H
i - i^{th} or inlet
I - building interior
n - number of apertures
N - iteration number
o - outlet
r - reference
ref - reference

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ACKNOWLEDGMENT

We appreciate the financial support of ASHRAE for funding this research (ASHRAE research project 448). We thank Mr. William Seaton, manager of ASHRAE research, for his cooperation throughout the project. We are grateful to the ASHRAE project monitoring committee--Fred Bauman, Tamami Kusuda and Chip Barnaby for their helpful advice and suggestions. We also would like to thank Bishri Abdel-Hamid and Adel Kamel, both graduate assistants at the Florida Solar Energy Center, for their assistance in data analysis.

APPENDIX A

CALCULATION PROCEDURE FOR DETERMINING VENTILATION RATES

Steps to be followed in order to calculate ventilation airflows for a known building are given here. Figure A-1 gives the flow chart of the steps necessary. Section A.1 provides a list of definitions for easy reference.

The assumptions inherent in this calculation procedure are:

1. No stack effect.
2. No pressure drop inside building, negligible effects due to partitions.
3. Perfect mixing.
4. Wind profile can be described by power law.
5. Use of Cp data on an average wall basis for low-rise buildings.
6. Valid for window or other wall apertures only, not for roof level apertures.

STEP 1: Get wind, building, and terrain data. The following data should be known in this step.

Terrain data

- h : mast height in the reference terrain (ft)
- V_{rh} : wind speed in the reference terrain at height h, (ft/s)
- a_r & b_r : terrain constants of the reference terrain (See Table A-1)
- a_b & b_b : terrain constants of the building terrain (See Table A-1)

Building data

- L : Longer side dimension of building (ft)
- W : Small side dimension of building (ft)
- H : Reference height (ft)
  - Average window height for tall buildings
  - Eave height for low rise buildings (up to 3 stories)

Window parameters

A_i: Area of the i^{th} window (ft^2)
It is defined as the open window area. For sliding or hung windows, open window area is typically 40% of the rough opening in the wall. For fully operable windows (e.g., awnings or casement windows) assume A_i to be the entire glazed area. The window may or may not have insect screening. Correction factors for insect screening or awning window blockage when open are given later in Step 6 of this section.

XL and ZH: The dimensionless horizontal and vertical location of each window on the wall (required for tall buildings only - see Figure 8 and definitions).

STEP 2: Using H as the reference height, calculate the reference velocity (V_{ref}) at this reference height using procedure outlined in Section A.2.

STEP 3: Choose one of the following:

1. If all windows are on a single wall, determine the total window area (A). Go to Step 4.
2. If low-rise building:
   - -- Sum window areas on each wall and treat them as single windows.
   - -- Follow procedure in Section A.3 and determine C_p for each wall.
3. If high-rise building: Follow procedure in Section A.3 and determine C_p for each window location.

STEP 4: Choose one of the following:

1. Use procedure A outlined in Section A.5 for single windows
2. Use procedure B outlined in Section A.6 for one window each on two walls
3. Use procedure C outlined in Section A.7 for windows on three or more walls

STEP 5: Choose one of the following:

1. **If procedure A was used in step 4, ignore this step.**
2. **If procedure B or C was used, apply the following correction to account for window aperture.**

$$Ca = CQ/(1+CQ) \tag{A-1}$$

where

Ca - is the actual flow coefficient
CQ - is the flow coefficient calculated in procedures B or C

Calculate airflow (in ft^3/s):

$$Q = Ca\ V_{ref}\ A_e \tag{A-2}$$

STEP 6: Correct for window type and insect screening by multiplying the flow by the following factors.

1. **Fully open awning window, no screen: 0.75**
2. **Awning window and 60% porosity insect screen: 0.65**
3. **60% porosity insect screening: 0.85**
4. **No data available for blockage in casement windows when the winds are at an oblique angle.**

STEP 7: Calculate air change per hour, ACH

$$ACH = \frac{Q}{ZV * 3600} \tag{A-3}$$

ZV - Zone Volume (ft^3)

STEP 8: Apply correction for surrounding effects to the flow from Section A.4. If ACH is less than 3 use ACH = 3. Note that this value is based on measured ACH in two field residences with windows fully open on windless nights.

A.1 DEFINITIONS

The definitions of the various parameters used in the calculation procedure are summarized here.

1. Pressure coefficient (C_p): This dimensionless quantity is defined as:

$$\frac{p - p_r}{1/2\ \rho\ V_{ref}^2}$$

p - local pressure on a surface measured by a pressure tap flush with the building surface (psf)

p_r - reference free stream static pressure (psf)

ρ - air density (lb/ft^3)

V_{ref} = reference wind speed at a reference height or free stream velocity (ft/s)

2. Wind Angle (α): The angle (in degrees) between the wind direction and the outward normal of the wall under consideration (See Figure 1).

3. Side Ratio (S): The ratio of the width of the wall under consideration to the width of the adjacent wall (see Figure 1).

4. Effective Area (A_e): Effective window area (ft^2). Definition differs for different cases. For buildings with windows on only one wall or windows on three or more walls, Ae is the sum of all window areas. For problems with windows on two walls see Section A.6.

5. Terrain Constants (a's and b's) : The values of a's and b's chosen from Table A-1, which define the terrain characteristics.

6. Length Ratio (XL): The dimensionless horizontal location of a point on a wall. It is the ratio of the horizontal distance of the point from the edge of the wall to the length of the wall (see Figure 8).

7. Height Ratio (ZH): The dimensionless vertical location of a point on a wall. It is defined as the ratio of the distance of the point from the ground to the height of the wall (see Figure 8).

8. Long wall : of a rectangular building is the wall having the larger side dimension
Short wall : of a rectangular building is the wall having the smaller side dimension

9. Roof angle γ : is the roof slope (degree) of the roof parallel to the wall for which C_p is sought

10. Roof angle δ : is the roof slope (degree) of the roof perpendicular to the wall for which C_p is sought.

A.2 DETERMINATION OF REFERENCE VELOCITY

The following data must be known

Reference terrain parameters

- h : mast height in the reference terrain (ft)
- V_{rh} : wind speed in the reference terrain at height h (ft/s)
- a_r & b_r : Terrain constants of the reference terrain (Table A-1)

Building terrain parameters

- H : height in building terrain where Vref is required (ft)
- a_b & b_b : terrain constants of the building terrain (Table A-1)
- $V_{ref} = V_{bH}$: The reference velocity (ft/s) at the height (H) in the building terrain. This is the reference velocity that has to be determined and used in the calculation procedure.

$$V_{ref} = V_{bH} = [(33/h)^{**}b_r]^*[(H/33)^{**}b_b]^*(a_b/a_r)^*V_{rh} \qquad (A\text{-}4)$$

A.3 PRESSURE COEFFICIENTS

This section gives the procedure for obtaining C_p through the curve fit equations for both low-rise and high-rise buildings.

Low-rise Building

1. For each wall, determine the appropriate side ratio (S) according to definitions.

2. For each wall, determine the wind incidence angle (α) according to definition.

3. Use Equation 1 and its coefficients given in Equation 2 to calculate the normalized C_p (NC_p) for each wall.

4. From the normalized C_p value, calculate the actual C_p by multiplying the normalized value by the C_p at zero incidence. Use C_p at zero incidence to be 0.6.

5. If a garage or wingwall is present on a wall, modify C_p for that wall as illustrated in Figure 6.

6. If the house is U-shaped, modify C_p for the inner walls of the U as illustrated in Figure 7.

Note that all data in literature are for rectangular buildings. Steps 5 and 6 above are authors' recommendation on what to do for realistic house plans.

High rise Building

1. For each window, determine its location in terms of XL and ZH and the applicable side ratio (S) according to definitions.

2. For each window, determine the wind incidence angle (α) according to definition.

3. Use Equation 4 and its coefficients given in Equation 5 to calculate the actual C_p for each window.

A.4 CORRECTIONS FOR SURROUNDING EFFECTS

Corrections are to be applied to the ventilation flow rate calculated in step 7 of the calculation procedure, based on the general shielding class in which the building is located and correction factors of Table 2 and Equation 3.

Note that these correction factors should be applied to the ventilation flow rate and not C_p.

A.5 PROCEDURE A: SINGLE WINDOW

The formula for calculating ventilation rates through a single window is given by:

$$Q = 1.766\ A\ V_{ref} \quad (A-5)$$

where

Q - is the airflow (in ft^3/s)

A - is the open aperture area of all windows on that wall (in ft^2)

V_{ref} - is the wind speed (ft/s) at the building site at reference height. For low-rise buildings, use eave height as reference height. For high-rise buildings, calculate airflow separately for each floor using ceiling height of that floor as the reference height.

The reference wind speed at the site reference height can be calculated from meteorological data using the procedure outlined in Section A.2.

A.6 PROCEDURE B: ONE INLET AND ONE OUTLET

The procedure for calculating the flow through a cross ventilated building with one effective inlet and one effective outlet is presented here. The procedure can be used for a low rise building having windows on two walls or for a high- rise building having one window each on two walls.

The airflow coefficient in such rooms can be expressed as

$$CQ = Q/(A_e V_{ref}) = Cd\ (\Delta C_p)1/2 \qquad \text{(A-6)}$$

where

CQ is the flow coefficient

Q is the flow (ft^3/s)

A_e is the effective window area (ft^2) $= A_o A_i/(A^2{}_o + A^2{}_i)^{1/2}$ (A-7)

where A_o and A_i are the open outlet and inlet areas respectively (ft^2)

Cd is the discharge Coefficient = 0.62 (recommended per Swami and Chandra 1987)

ΔC_p = Pressure coefficient difference across the inlet and outlet.

A.7 PROCEDURE C: MULTIPLE INLETS AND OUTLETS

The calculation procedure described here uses the Vickery (1983) model. The model starts with the standard orifice flow equation through the i^{th} aperture. Note: in this procedure, aperture means the sum of all open areas on a wall for low-rise buildings or an individual window for high-rise buildings.

$$Q_i = Cd_i\ A_i\ V_{ref} \frac{(Cp_i - Cp_I)}{|Cp_i - Cp_I|^{1/2}} \qquad \text{(A-8)}$$

where

Q_i = Flow through the i^{th} aperture (ft^3/s)

Cd_i = Discharge coefficient for the ith aperture 0.62 (recommended value, Swami and Chandra 1987)

A_i = Area of the ith aperture (ft^2)

V_{ref} = Reference velocity (ft/s)

Cp_i = Pressure coefficient for the ith aperture

Cp_I = Internal pressure coefficient (unknown)

The numerator and denominator are written specifically to account for inflows and outflows. Equation A-8 is nondimensionalized by V_{ref} and (effective) area A_e (where A_e is the sum of all window areas in ft^2) such that Equation A-8 is recast as:

$$\Delta CQ_i = Cd_i \frac{A_i}{A_e} \frac{(Cp_i - Cp_I)}{|Cp_i - Cp_I|^{1/2}} \qquad \text{(A-9)}$$

An iterative solution (since Cp_I is unknown) is obtained as follows:

(i) Define two starting values of Cp_I as

$$(Cp_I)_1 = 1/n \, \Sigma Cp_i \qquad \text{(A-10)}$$

where

n = number of apertures

and

$$(Cp_I)_2 = (Cp_I)_1 + .01 \qquad \text{(A-11)}$$

and compute the corresponding values of net inflow Σ_1, and Σ_2 where, net inflow for the N^{th} iteration,

$$\Sigma_N = \sum_{i=1}^{n} \Delta CQ_i$$

(ii) Compute a new estimate $(Cp_I)_N$, for the N^{th} iteration, from the relationship;

$$(Cp_I)_N = (Cp_I)_{N-1} + \frac{\Sigma_{N-1}}{\Sigma_{N-2} - \Sigma_{N-1}} \left((Cp_i)_{N-1} - (Cp_I)_{N-2} \right) \qquad \text{(A-12)}$$

(iii) Compute the corresponding value of the net inflow,

Σ_N, and test $|\Sigma_N| < 10^{-4}$.

If yes: put $Cp_I = (Cp_I)_N$ and compute the elemental flow coefficients ΔCQ_i
If no : return to (i)

The flow coefficient into the building can then be evaluated by summing ΔCQ_i over all positive values, while the flow through a given surface of a high-rise building can be obtained by an algebraic sum over the regions comprising that surface.

$$CQ = \Sigma \Delta CQ_i \quad \text{for all positive } \Delta CQ_i \qquad \text{(A-13)}$$

A.8 EXAMPLE

A sample calculation comparing predicted and measured ventilation rates is presented here Chandra (1983) provides measured data for the FSEC PV house for three different wind directions. The ventilation rate for one wind direction is calculated here. Figure 10 is a plan of the experimental house, showing the window locations and areas (in ft^2). The window areas are open aperture areas with insect screening. The zone volume is 9300 ft^3. A uniform discharge coefficient of 0.62 was assumed.

Wind direction 87 degrees (north = 0°, east = 90°, south = 180°, west = 270°)

Step 1:
h = 33 ft
V_{rh} = 8.2 ft/s

From Table 2:
a_r = 1/0
b_r = 0.15
a_b = 1.0
b_b = 0.15

Since the meterological data were collected on site, the constants for the reference terrain and the building terrain are the same. This may not be the case if, for example, the meterological data are taken from the airport and the building is situated far away in a development.

H = 7.66 ft

Step 2:
V_{ref} = 8.2*(7.66/33)**0.15 = 6.6 ft/s

Step 3:

Windows	South	East	North	West
Area (ft^2)	16.91	10.67	15.3	2.66
Wind angle (α deg)	93	177	87	42
Side ratio (S)	1.56	0.64	1.56	0.64
0.6* NC_p (from Equation 1)	-0.337	-0.337	-0.253	0.347

Correction for the presence of the garage is applicable to the north wall. The C_p for that wall is modified to 0.6 as per Figure 6.

Steps 4 and 5:
Procedure C was programed into a computer that directly gave the air change per hour (ACH) given all previous inputs. The result from the procedure is ACH = 22.56.

Steps 6 through 8:
The correction factor for insect screening = 0.85
SCF = 0.88 (assuming Class II shielding of Sherman and Grimsrud)

Corrected ACH = 22.56*0.88*0.85 = 16.9
Measured = 19.0 (Chandra 1983)
% difference = -11%

TABLE 1

Source of Data Showing Model and Terrain Characteristics and C_p at Zero Incidence Referenced to Eave Height

Source		L:W:H	Model Roof	Terrain	C_p at zero incidence long wall	short wall
JENSEN	(1965)	2:1:1	flat roof	Open	.500	.559
JENSEN	(1965)	2:1:1	flat roof	Industrial	.600	.616
JENSEN	(1965)	2:1:1	1:1 roof	Open	.592	.599
JENSEN	(1965)	2:1:1	1:1 roof	Industrial	.685	.599
JENSEN	(1965)	2:1:0.5	1:1 roof	Industrial	.913	.952
CERMAK	(1981)	36:36:24	1:2 roof		.621	.609
HAMILTON	(1962)	1:1:1	flat roof	Suburban	.610	.610
HAMILTON	(1962)	1:1:1	15 deg roof	"	.511	.548
HAMILTON	(1962)	1:1:1	30 deg roof	"	.476	.493
HAMILTON	(1962)	1:1:1	45 deg roof	"	.546	.536
VICKERY	(1983)	100:80	1:12 roof	Open	.564	.518
VICKERY	(1983)	125:80	4:12 roof	Open	.403	.253
VICKERY	(1983)	125:80	1:12 roof	Open	.448	.495
VICKERY	(1983)	125:80	12:12 roof	Open	.479	.186
VICKERY	(1983)	125:80	4:12 roof	Suburban	.384	.281
VICKERY	(1983)	125:80	1:12 roof	"	.394	.311
VICKERY	(1983)	125:80	12:12 roof	"	.523	.168
WIREN	(1985)	130:85:52	1:1 roof	Open	.635	.722
LUSCH	(1964)	4:2:1	0 deg roof		.628	.600
LUSCH	(1964)	4:2:1	10 deg roof		.600	.580
LUSCH	(1964)	4:2:1	20 deg roof		.600	.620
LUSCH	(1964)	4:2:1	30 deg roof		.740	.620
LUSCH	(1964)	4:2:1	40 deg roof		.660	.720
LUSCH	(1964)	4:2:1	60 deg roof		.772	.900
ASHLEY	(1984)	8:1:0:5	flat roof	Suburban	.690	630
ASHLEY	(1984)	10:3:1:5	20 deg roof	"	.727	.674
ASHLEY	(1984)	2:7:1:0:5	24 deg roof	"	1.209	.817
AKINS	(1979)	1:1	flat roof	"	.613	.613
AKINS	(1979)	2:1	flat roof	"	.613	.613
AKINS	(1979)	4:1	flat roof	"	.613	.613

Note: Where building height is not specified, the C_p was obtained at by averaging the data from models of the same side ratio but different heights. Long and short walls refer to the larger and shorter building side.

TABLE 2

CORRECTION FACTORS FOR GENERALIZED SHIELDING

Shielding Class	Correction Factor (SCF)	Description
I	1.0	No obstruction or local shielding
II	0.88	Light local shielding with few obstructions (e.g., a few trees or a shed in the vicinity)
III	0.74	Moderate local shielding; some obstructions within two house heights (e.g., thick hedge or fence and nearby buildings)
IV	0.57	Heavy shielding; obstruction around most of perimeter building or trees within five building heights in most directions (e.g., well developed tract houses)
V	0.31	Very heavy shielding; large obstruction surrounding perimeter within two house heights (e.g., typical downtown area)

TABLE 3

COMPARISON OF PREDICTED AND MEASURED ACH

	Wind dir. (degrees)	Wind Speed at 10m (mph)	Measured ACH (1982)	Calculated ACH	% Diff.
1	87	5.6	19.0	16.9	-11
2	140	9.7	29.8	29.9	0.4
3	152	7.1	23.3	22.5	-3.2

TABLE A-1

TERRAIN PARAMETERS FOR STANDARD TERRAIN CLASSES

Class	b	a	Description
I	0.10	1.30	Ocean or other body of water with at least 5 km of unrestricted expanse
II	0.15	1.0	Flat terrain with some isolated obstacles
III	0.20	.85	Rural areas with low buildings
IV	0.25	0.67	Urban, industrial or forest areas
V	0.35	0.47	Center of large city

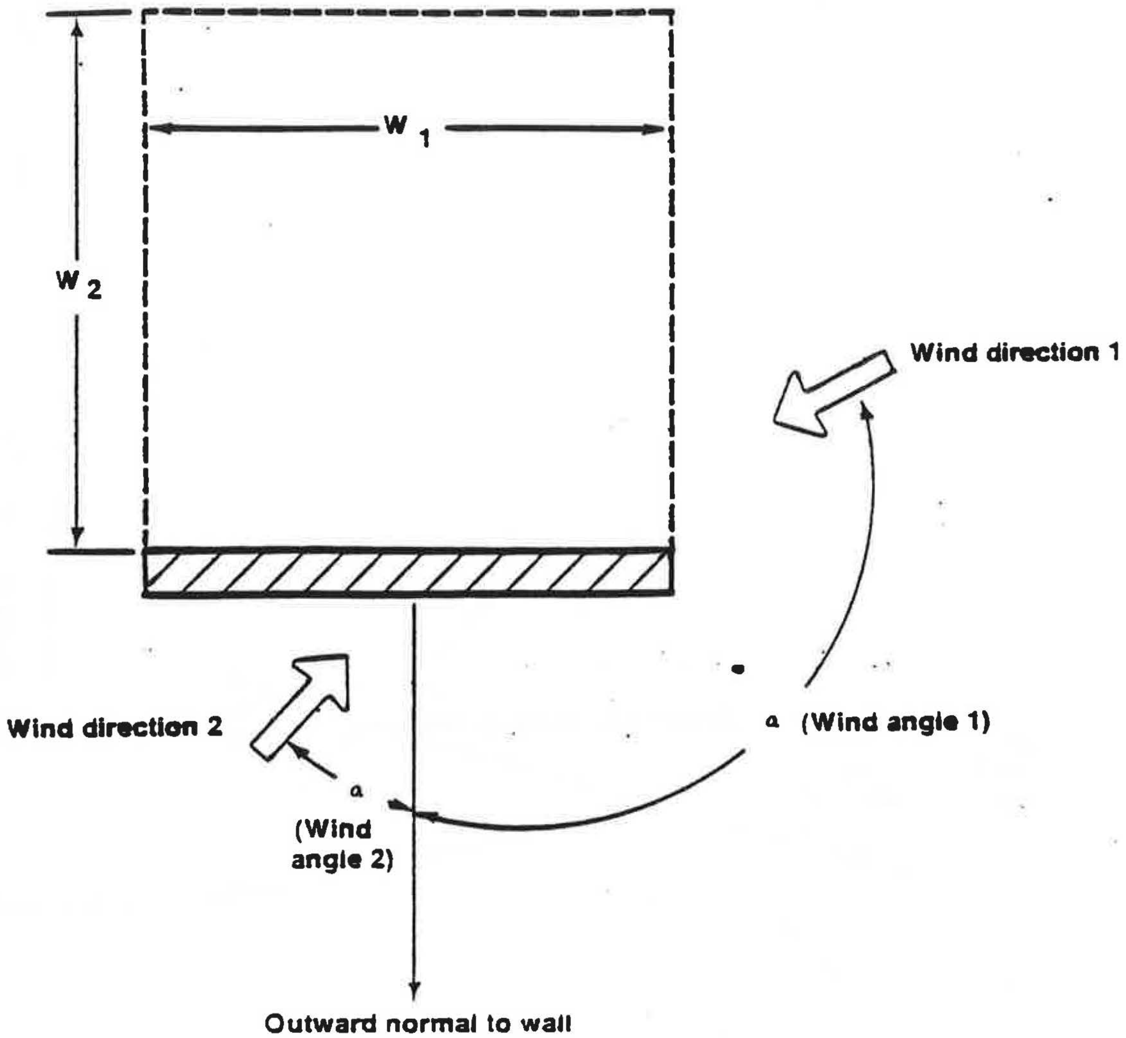


Figure 1. Conventions for wind angle (α) and side ratio (S)

Note: α : is the angle between the wind direction and the outward normal to the wall
S : is the side ratio ($=W_1/W_2$)
W_1 : is the width of the wall for which C_p is sought
W_2 : is the width of the adjacent wall

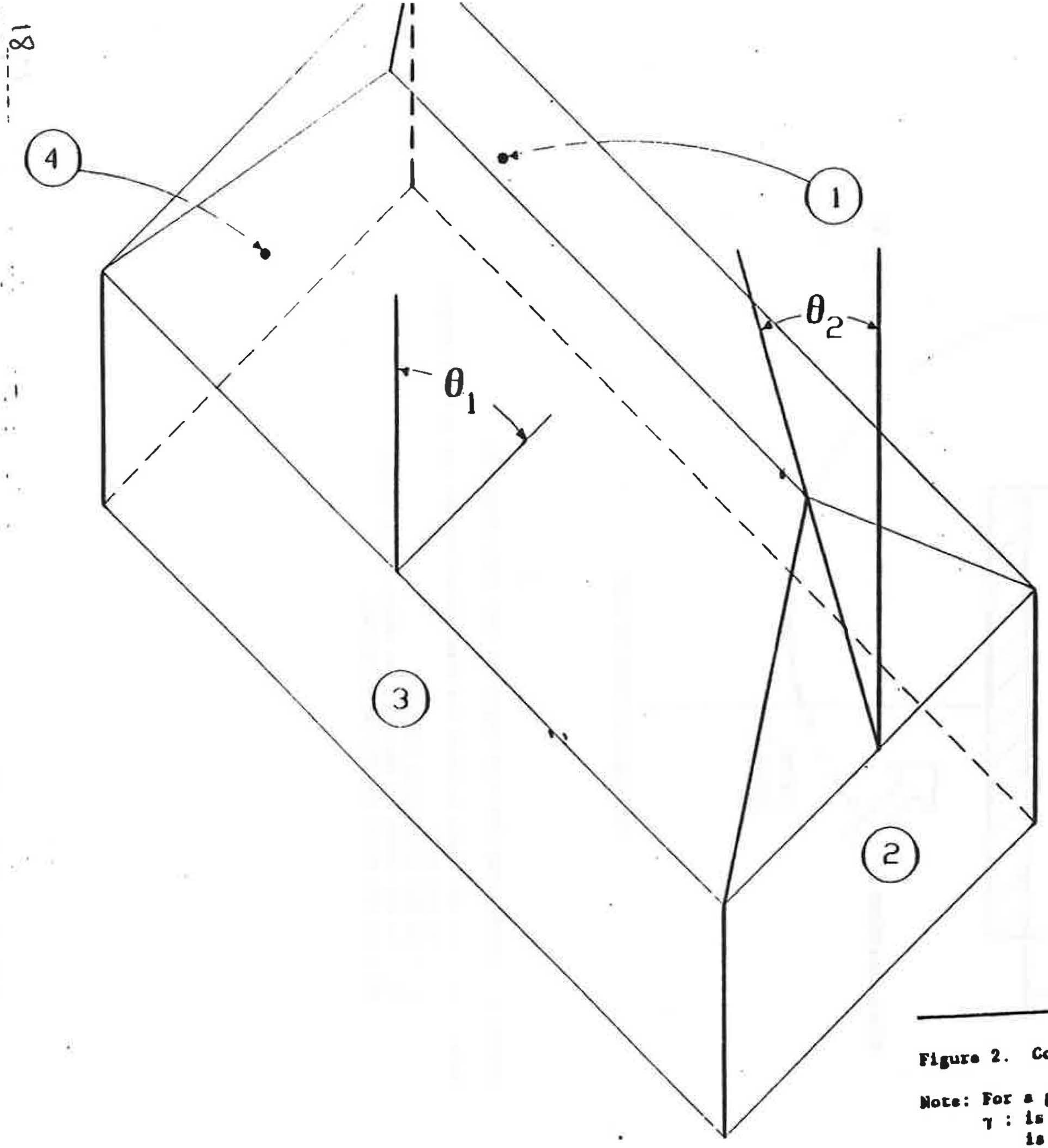


Figure 2. Conventions used in defining roof angles for each wall

Note: For a given wall two roof angles are definable (γ and δ)
- γ : is the roof slope of the roof parallel to the wall for which C_p is sought.
- δ : is the roof slope of the roof perpendicular to the wall for which C_p is sought.

Example, for wall 3, $\gamma = \theta_1$ and $\delta = \theta_2$
for wall 2, $\gamma = \theta_2$ and $\delta = \theta_1$

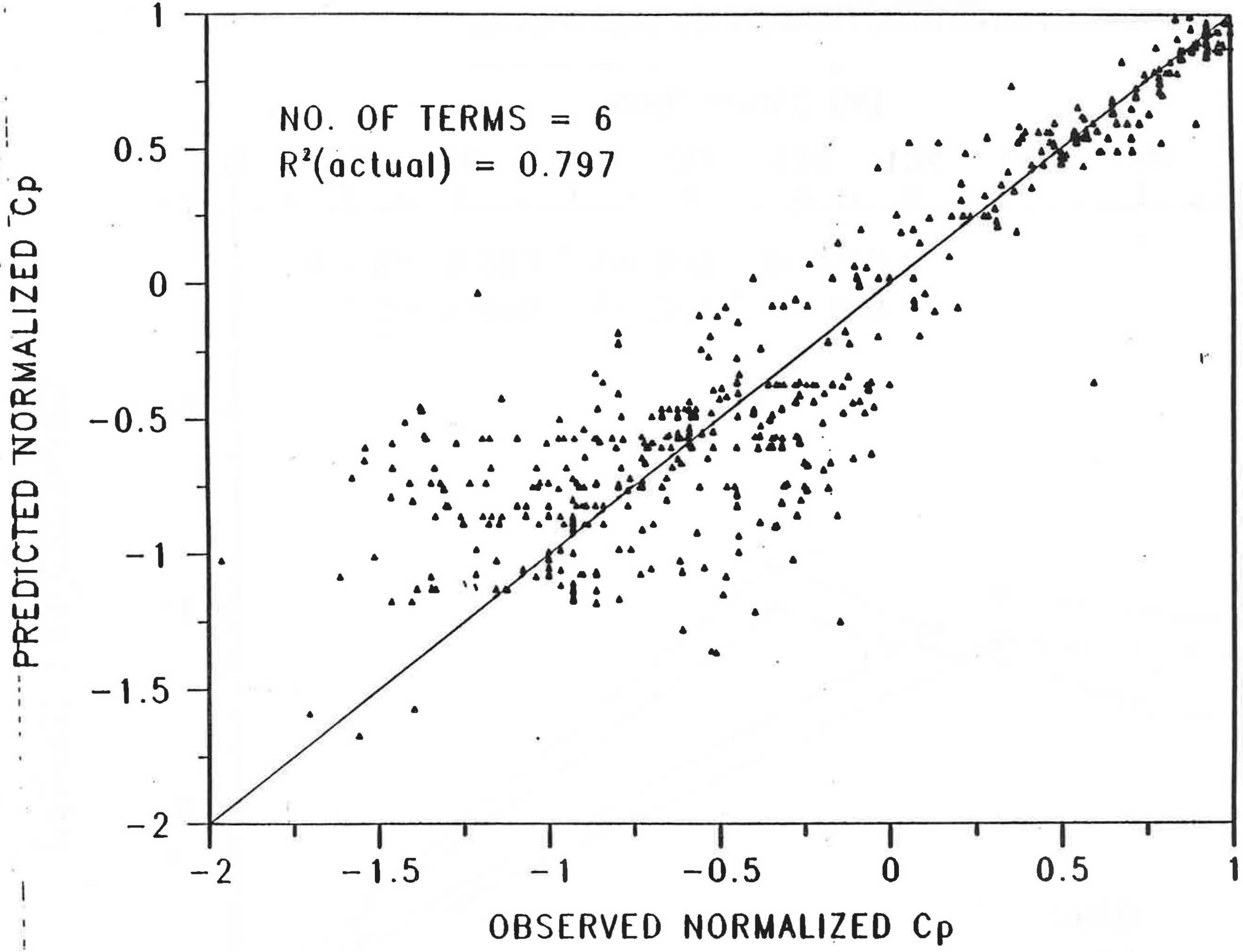


Figure 3. Correspondence of predicted and observed normalized C_p for low-rise buildings.

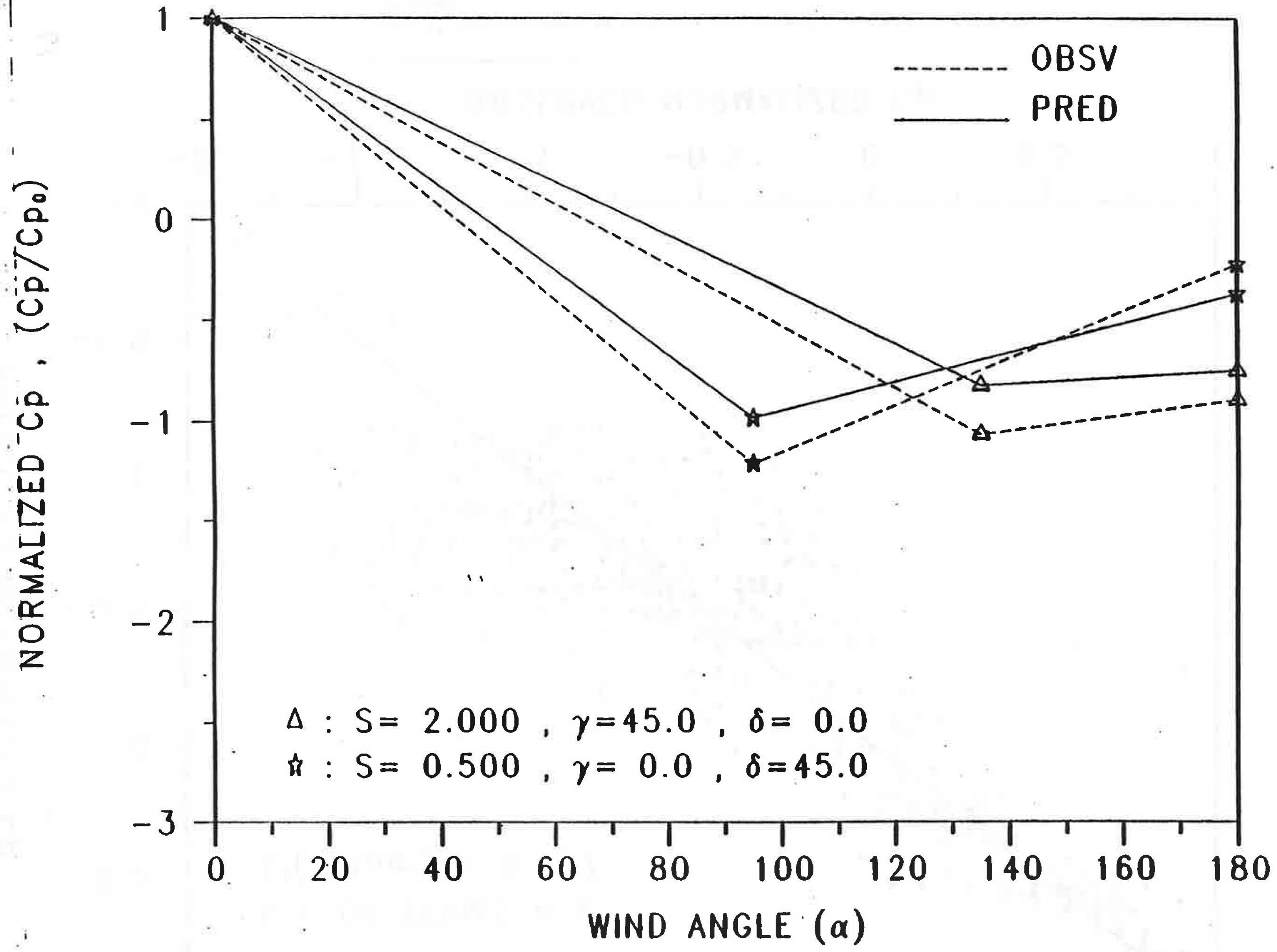


Figure 4. Comparison of our prediction with observed data from Jensen (1965) for 2:1:0.5 model house; 1:1 roof; and large turbulence.

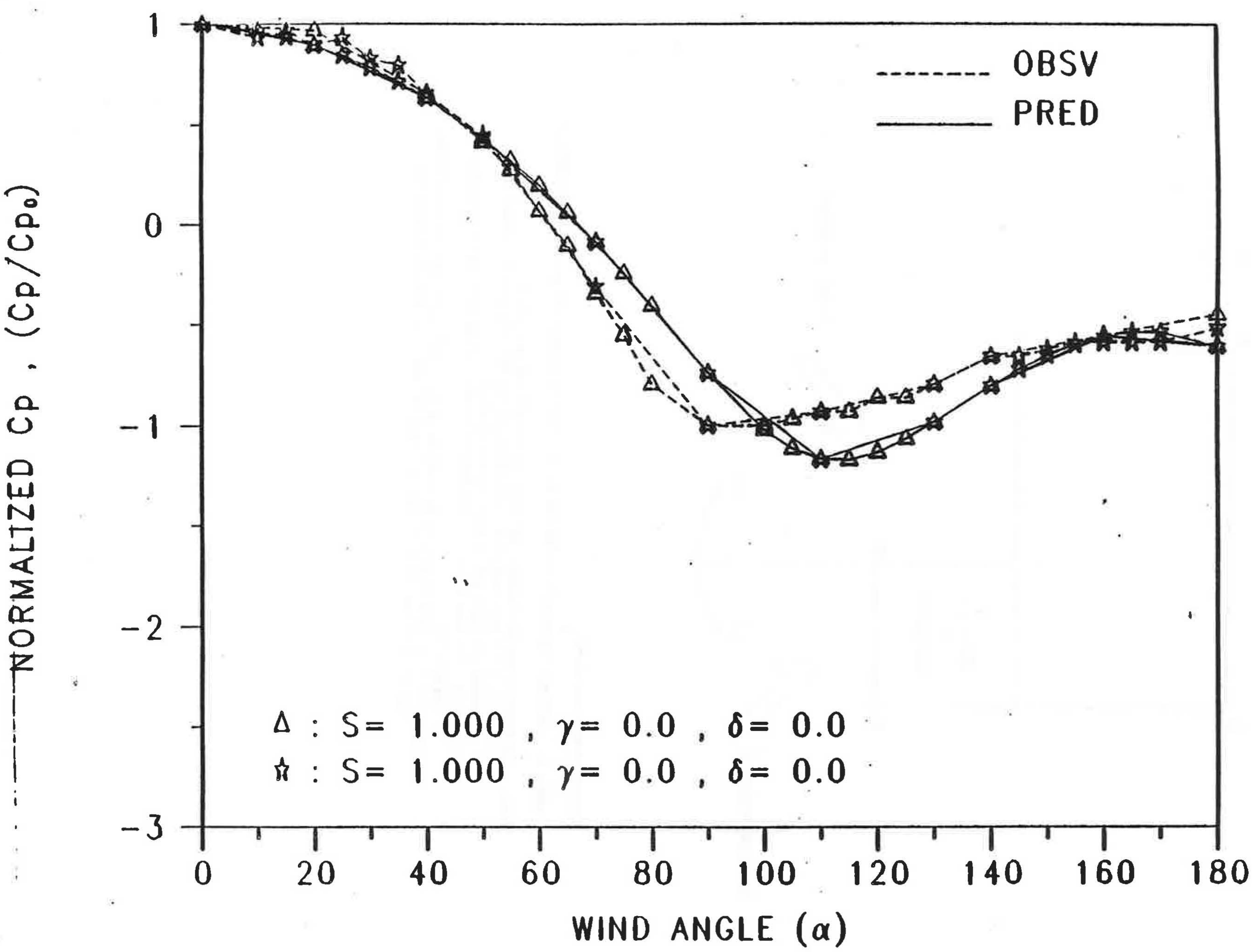


Figure 5. Comparison of our prediction with observed data from Akins (1979) for 1:1 model house; flat roof; and suburban terrain.

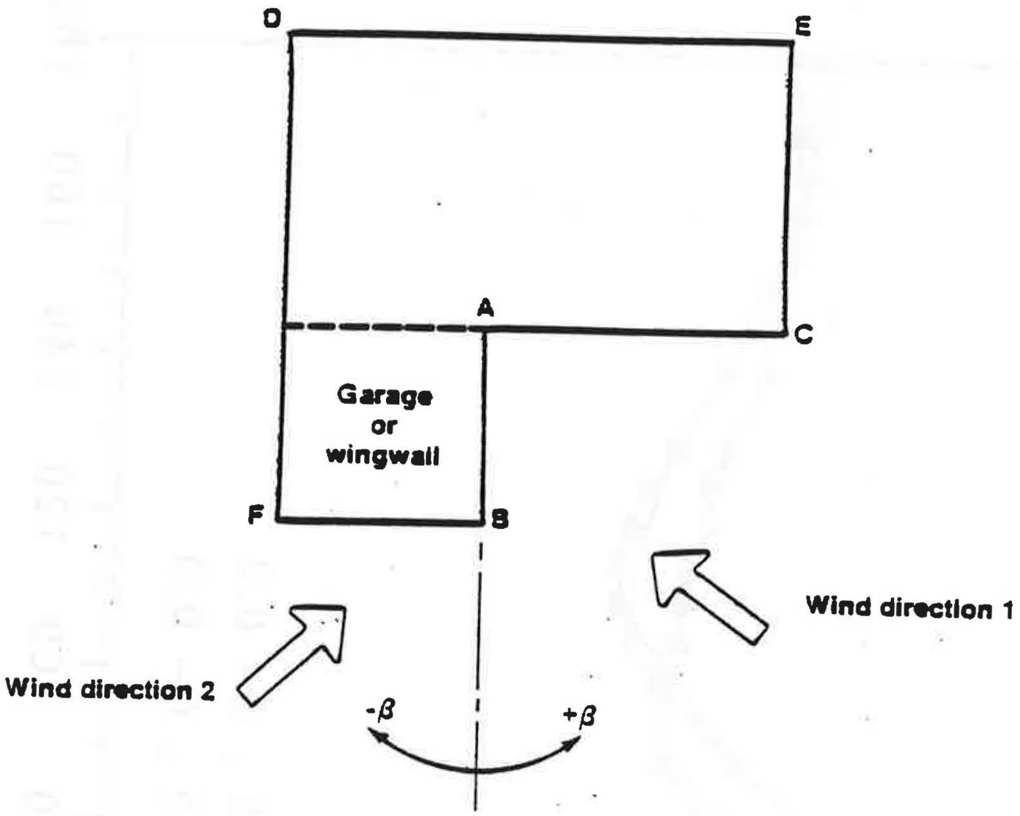


Figure 6. Correction/modification to C_p for the presence of garage or wingwalls.

Note: Correction/modification for wall AC should be as follows:

i. For β in the positive direction up to 90°, C_p may be taken as the value at zero incidence (i.e., C_p=0.6)

ii. For β in the positive direction greater than 90°, no correction is suggested.

iii. For β in the negative direction up to -90°, include the apertures in wall AC as if they are in wall EC and use normal equations.

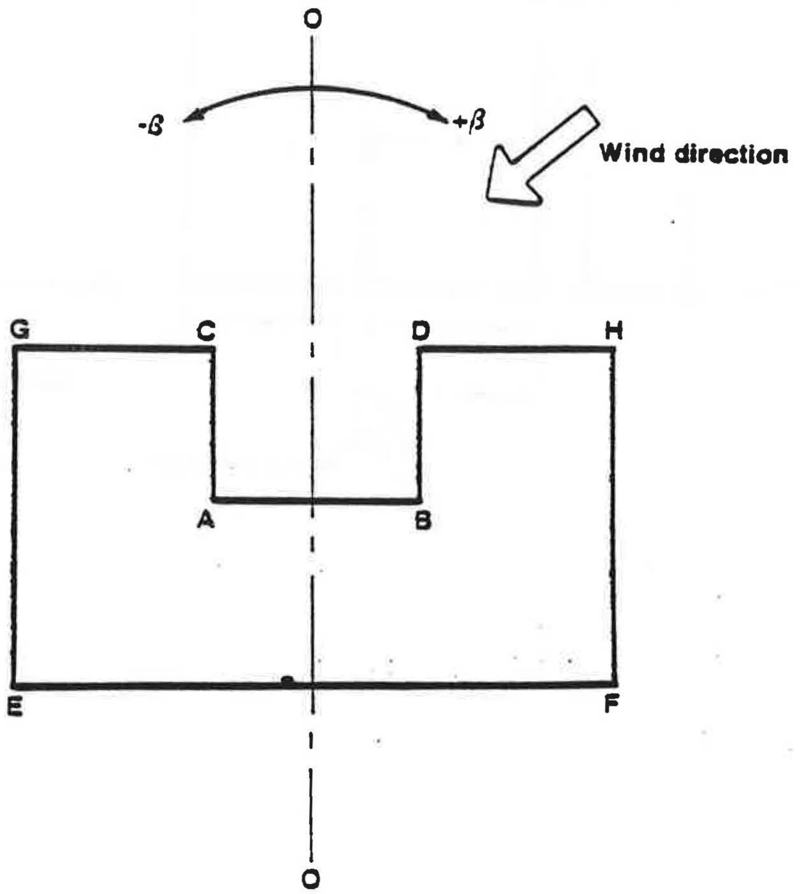


Figure 7. Modification to C_p for U-shaped buildings.

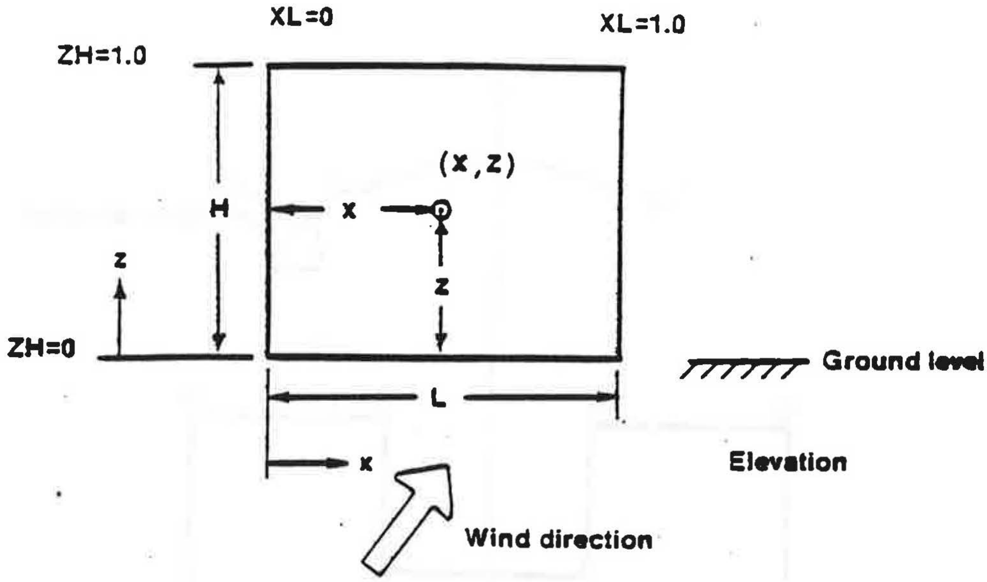
Note: the following modification to C_p for walls AB, AC and BD is suggested:

i. For angles β up to $\pm 45^o$, C_p for walls AB, AC and BD may be assumed to be the value at zero incidence (i.e., C_p = 0.6).

ii. For positive β up to 60°, walls AB and AC may be taken to at zero incidence (i.e., C_p = 0.6). Window(s) on wall BD may be added to those in wall EF.

iii. For negative β up to 60°, walls DB and AB may be taken to be at zero incidence (i.e., C_p = 0.6). Window(s) in AC may be added to those in wall EF.

iv. For angle β beyond $\pm 60^o$, the apertures in all three walls should be treated as if they are in leeward region. Thus, add all the aperture areas in wall AC, AB and BD and include them as areas in wall GE for $\beta > + 60^o$, and in wall HF for $\beta < - 60^o$.



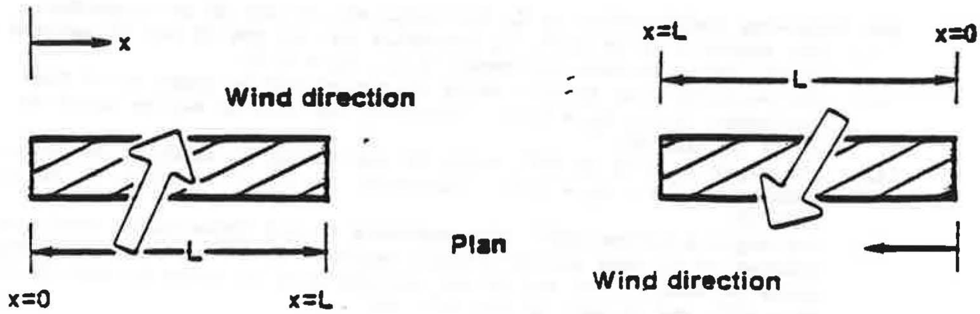


Figure 8. Definition of XL and ZH for tall buildings.

Note: Length ratio XL = x/L
Height ratio ZH = z/H
z = 0 is always the ground level (see elevation)
x = 0 must be taken as the edge closer to the tail of the wind (see plan).

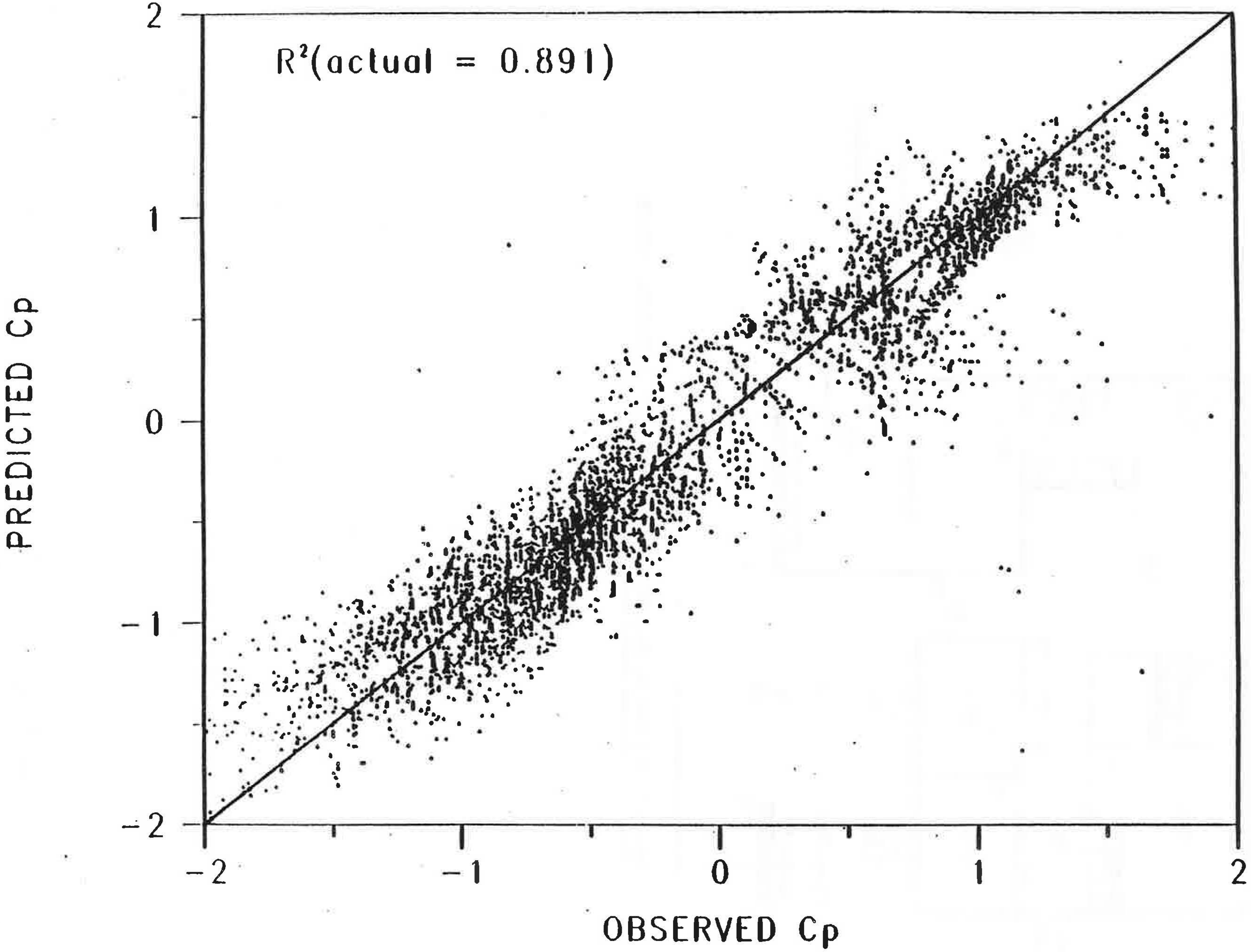


Figure 9. Correspondence of predicted and observed C_p for tall buildings.

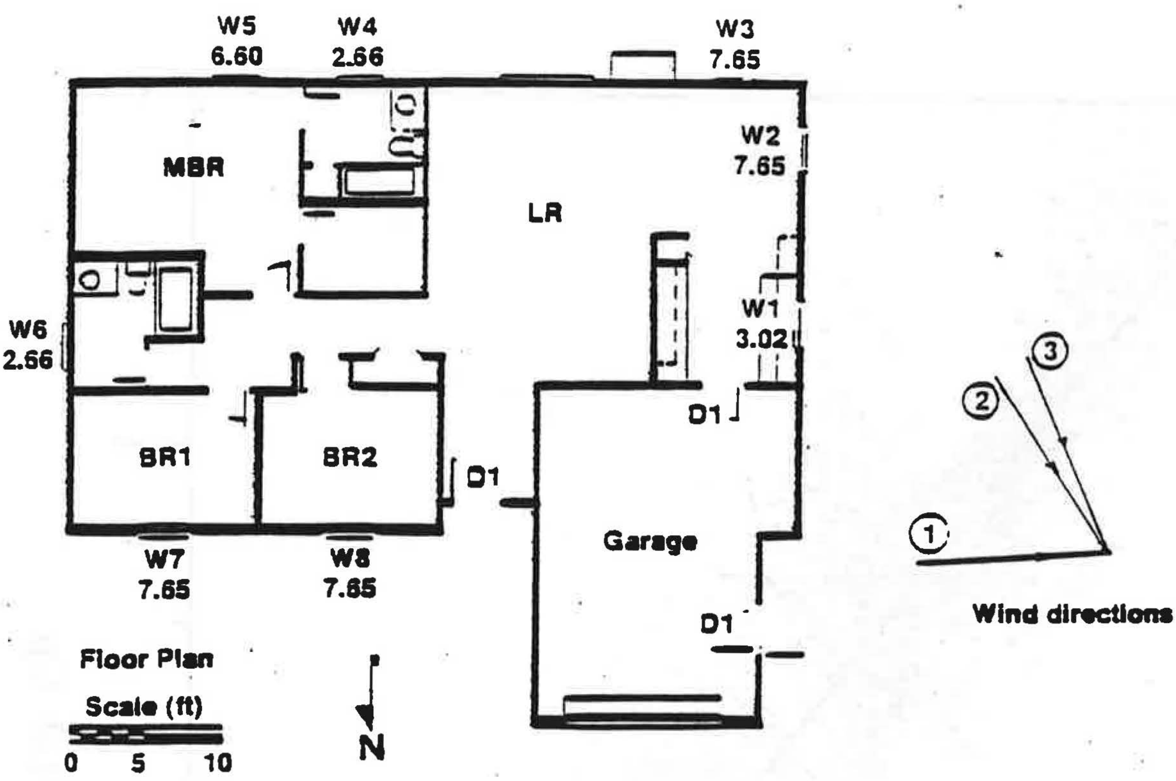


Figure 10. The plan of the house used for ventilation experiments, showing window location and window areas (in sq. ft.).

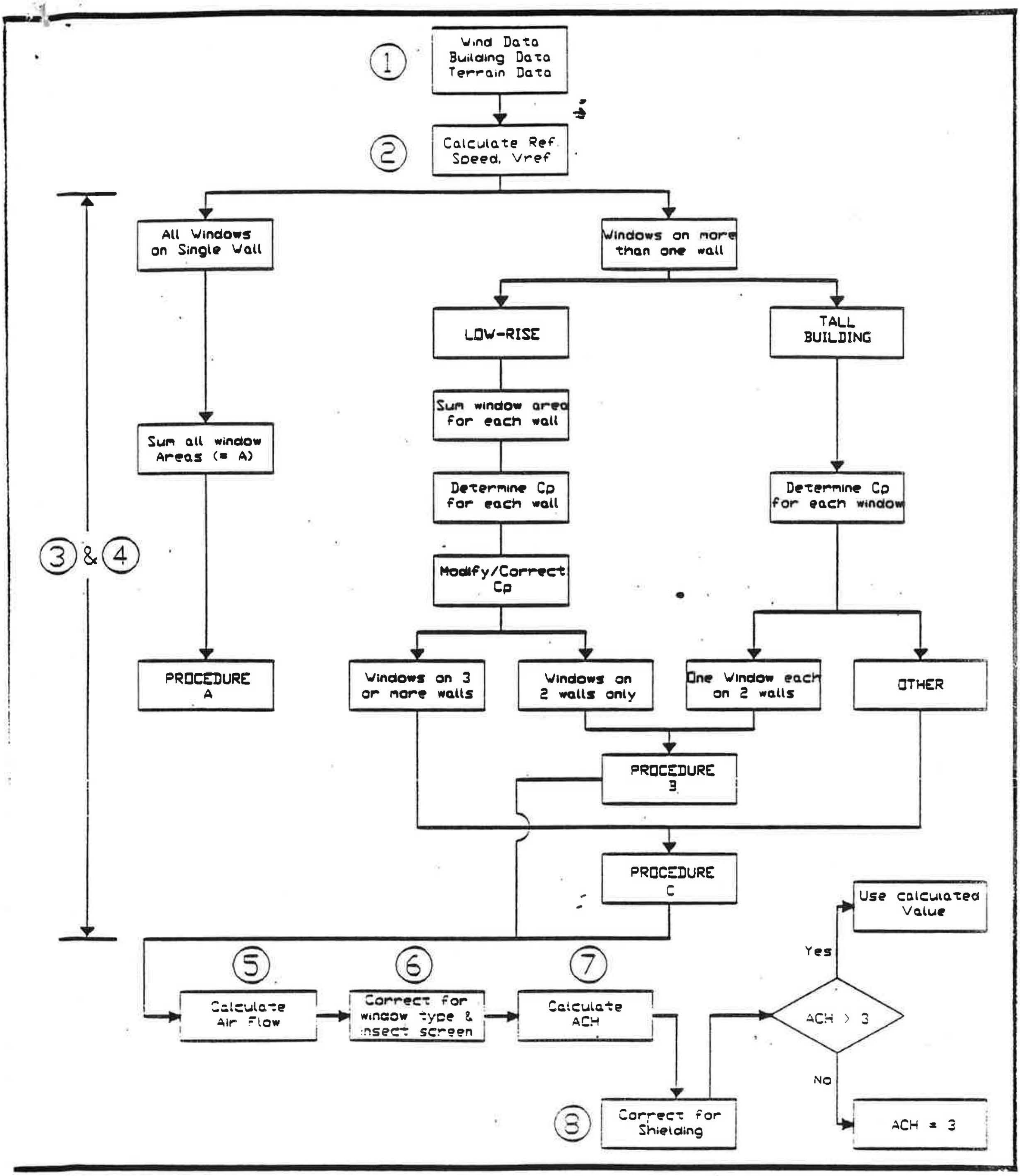


Figure A-1. Flow chart for the calculation procedure.