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# WIND PRESSURES ON FLAT ROOF EDGES AND CORNERS WITH AND WITHOUT PARAPETS

VIOREL-LUCIAN MUNTEANU-BADIAN

A Thesis

in

The Centre

for

Building Studies

Presented in Partial Fulfillment of the Requirements
for the Degree of Master of Applied Science
at
Concordia University
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April 1992

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# ABSTRACT

## Wind Pressures on Flat Roof Edges and Corners With and Without Parapets

Wind Standards and Codes of Practice rarely refer to the effects of parapets on the wind-induced roof pressure coefficients. In fact, there has been a limited number of studies dealing with the actual effect of parapets on the wind loads acting on buildings.

This thesis reports systematic research to evaluate the wind loads on flat roof edges and corners on buildings with and without parapets, with the results of an experimental study carried out in the Building Aerodynamics Laboratory of the Centre for Building Studies. The basic model is a flat roof square building with an assembly of 224 taps distributed on one corner and along its adjacent edges. It has been tested in the boundary layer wind tunnel for wind blowing over simulated open country and suburban terrains.

Mean, peak and root mean square values of the wind pressure were recorded using both local and area-averaged load measurement techniques. The high density of pressure taps allowed a detailed investigation of the effect of the tap's distance from the edge of the roof, as well as the effect of parapets height on the pressure coefficient measured.

The experimental results indicate that a small difference in the location of a pressure tap may yield pressure coefficients more than 100% different for some particular oblique wind directions. It also indicates that roof corners suffering the majority of failures are affected by a significant increase on both mean and peak suctions for both building heights having low parapets ($h < 1$m). The influence of parapets on the wind-induced loads on buildings' roofs appears to be independent of the terrain roughness.

Applying the results in practice reveals that the new specifications after the Supplement of N.B.C.C. (1990) for wind loads on buildings with parapets are adequate for roof corner areas.
Some suggestions for Wind Standards and Codes are made.

# ACKNOWLEDGEMENT

The author wishes to express his sincere gratitude to his thesis supervisor, Professor Dr. Theodore Stathopoulos, for his advice, direction and continuous support throughout this study.

I wish to dedicate this work to my wife, composer Maya Badian.

## TABLE OF CONTENTS

Page

## LIST OF TABLES

# LIST OF FIGURES

# LIST OF PHOTOGRAPHS

# LIST OF APPENDIX

# CHAPTER 1

# INTRODUCTION

> "In Spite of all of the mathematical and engineering sophistication possible with a computer, WIND ANALYSIS has still managed to elude complete quantification"
>
> ....JACK E. CERMAK

## 1.1 GENERAL

Wind Engineering is a new and rapidly developing field. Wind effects on buildings and other structures have been studied systematically during the last 30 to 40 years. Development of construction methods, and the use of modern building materials have led towards light-weight and more unconventional architectural schemes for the present day buildings. The reliable prediction of wind response of buildings still seems to be a challenging task for researchers and scholars.

Actually, the complete destruction of buildings or structures by the wind is rare; but local failures, especially to the roofs and cladding elements, are more common and expensive. Wind engineers have carried out several investigations related to the effects of wind on building roofs. Standards of practice and Building Codes have also been established to specify appropriate wind loadings. However, wind loading on roofs is a complex problem and a closer view of the mechanism of roof wind loading seems to be necessary.

Much of the current knowledge relating to three-dimensional wind flows around buildings has been obtained by means of model tests in boundary-layer wind tunnels. An important publication based on wind-tunnel tests is Hunt, Abell, Peterka and Woo (1978). Figure 1.1 shows that the mean streamlines for flow about a single building form a complex flow geometry. The flow approaching the obstacle separates from the surface a distance upwind of the building. This separation location is dependent to the first order on building height-to-width ratio, building height-to-boundary-layer-height ratio and upstream surface roughness. The vorticity in this separated flow, in combination with the pressure distribution on the front of the building, results in downward flow on the front of the building. This subsequently causes the separated flow to roll up into a vortex. The vortex is wrapped around the building by

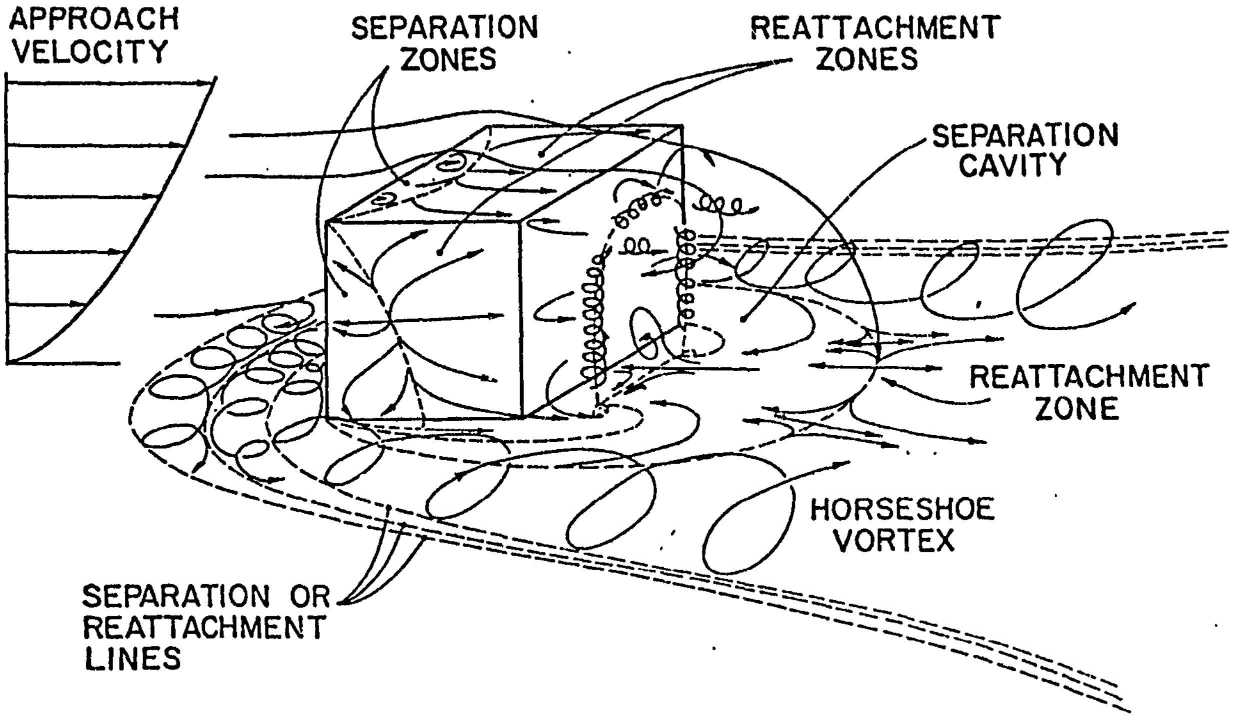
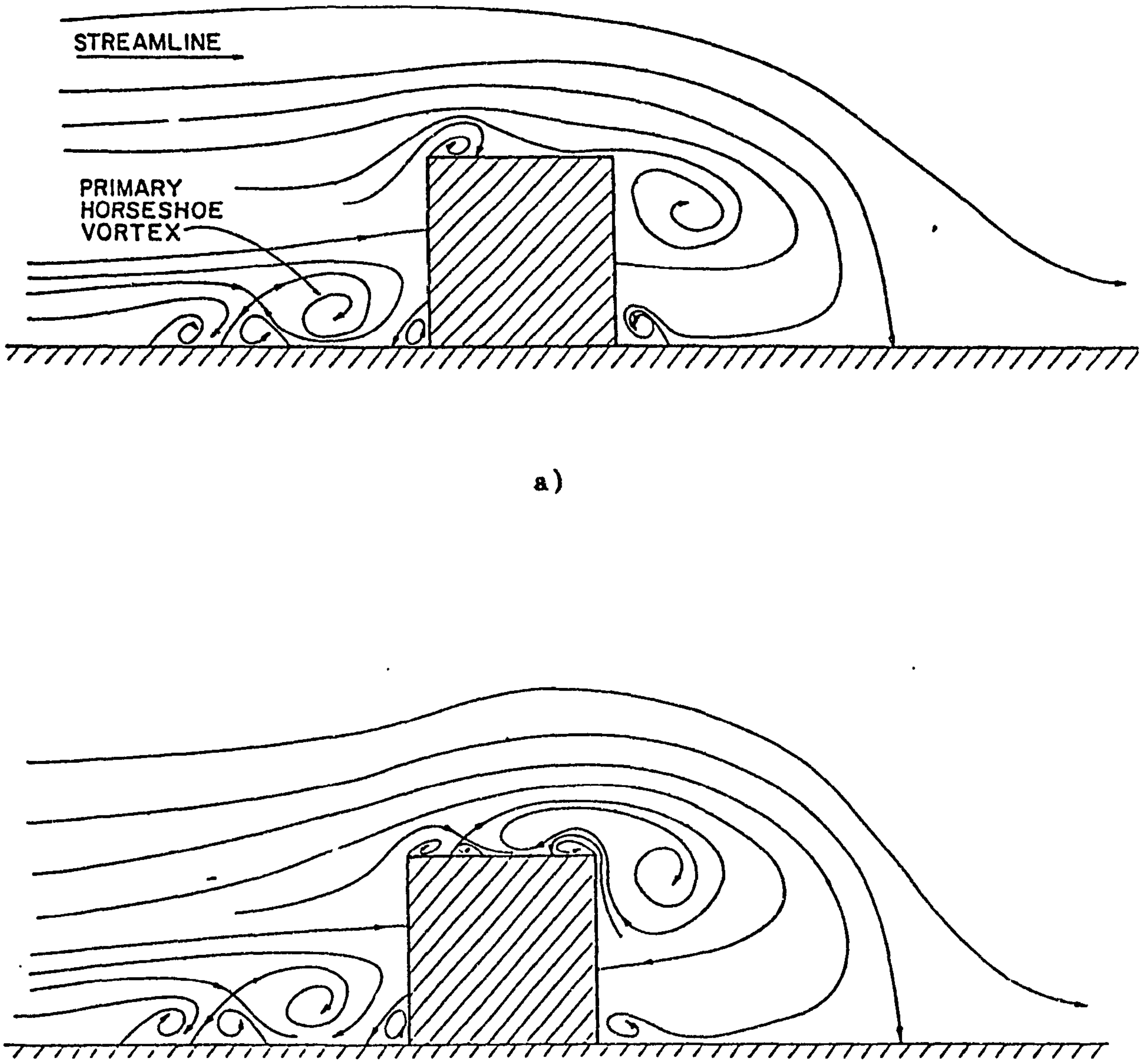


Fig. 1.1 MEAN STREAMLINE PATTERNS ABOUT A BUILDING
(Hunt, Abell, Peterka and Woo, 1978)

convection into a horseshoe shape. The primary vortex induces additional vortices of smaller size and strength, Figures 1.1 and 1.2 a), which are eventually incorporated into the primary vortex around the side of the building and lose their individual identity. The horseshoe vortex can be identified in the flow at some distance downwind.

The wind that impinges on the front of the building forms a stagnation region between 2/3 and 3/4 of the building height depending on building height-to-width ratio. From this region, flow moves outward toward all front edges of the building. The flow separates at the front edge of the top and sides and may or may not reattach to the top or sides before reaching the back edges. Reattachment depends on building length-to-width ratio, height-to-length ratio and upstream roughness (which determines the turbulence intensity in the approaching wind - a significant factor in distance to reattachment). Figures 1.1 and 1.2 a) show patterns for a reattached flow; 1.2 b) shows flow patterns for an unreattaching flow.

A separation cavity covers the rear face of the building and also the top and sides when reattachment on the sides does not occur. Examination of Figures 1.1 and 1.2 reveals that the mean streamline reattaching to the ground surface downwind of the building originates in the flow upwind of the building and not at a separation point on the building. The same is true of the streamline which forms a stagnation point on the rear face. Thus, the mean flow field convects mass directly into the separation



a)

b)

Fig. 1.2 CENTERLINE STREAMLINE PATTERNS FOR FLOW
a) REATTACHING TO TOP
b) NOT REATTACHING TO TOP
(Hunt, Abell, Peterka and Woo, 1978)

cavity, and, by continuity of mass, it also convects flow out of the cavity region. The direct convection out is more difficult to visualize but involves off-centerline flow departing from the two standing vortices with vertical axes forming an arch at the back corner and probably entrainment into the horseshoe vortex.
The organized picture of the cavity described above is made clody by the existence of a high level of turbulence in this region.

Some past investigators [Kind (1974), Kind and Wardlaw (1982), Kramer et al. (1985)] have also found that roof covering elements and various architectural features may have unique significant effects on the roof wind loadings. One of these elements, which is mostly used in practice, is the PARAPET.

## 1.2 PARAPETS ON ROOFS

It is common to see a low wall around the periphery of the building envelope. It is technically named "PARAPET". The parapet may be an extension of the vertical wall with less thickness or it may be fitted separately around the roof. The geometry of the parapets mostly depends on the dimensions of the buildings in order to give a better architectural look, to provide safety for people walking on the roof and to keep roof coverings in place. Usually, around 80 % of buildings have parapets on their roofs. However, the wind effects, induced by the parapets, have not received much attention. Even though the parapets are honoured as a roof safeguard element, their consequent wind effect on roofs for various building configurations may be significant. Note that while all Building Codes of Practice and Wind Standards have specifications for wind loads on roofs without parapets, only very few suggest provisions for the parapet effect. For instance, the Supplement to the National Building Code of Canada (1990) specifies that the corner coefficients (Cp.Cg for low buildings and Cp* for tall buildings) can be reduced for roofs with perimeter parapets having heights >1m.

The present study attempts to more accurately evaluate the effect of parapets on wind pressure acting on flat roof edges and corners, and to determine the actual magnitude of pressure coefficients by using a specially instrumented building model. A low building and an intermediate height building have been examined under the influence of several angles of attack of the wind. The assessment of wind loads under different exposure conditions has also been made.

Based on the experimental results, recommendations for roof corner wind loads with parapets have been made.

## 1.3 THESIS ORGANIZATION

The following chapter will discuss in detail the limited available work on this area and it will justify the need for the present study.

In Chapter 3, the characteristics of the simulated flow and the various configurations tested in the experiments are given. In addition, the data acquisition and instrumentation system of the Building Aerodynamics Laboratory of the Centre for Building Studies will be discussed.

Chapter 4 will present and analyze the results of the experimental study. The application of the results of the present study to the Wind Standards and Codes of Practice are presented in Chapter 5.

Finally, the conclusions and recommendations for further research in this topic are suggested in Chapter 6.

# CHAPTER 2

# LITERATURE REVIEW

> "Past experience has significant influence in the present achievements"
>
> ....A.G.DAVENPORT

## 2.1. DESCRIPTION OF EXISTING WORK

Only a limited number of studies were made in the past regarding the effect of parapets on wind-induced roof pressures. All of these studies were experimental and were carried out in wind tunnels.

The first among these studies was carried out by Leutheusser (1969) in a wind tunnel of the aeronautical type, more than two decades ago. The study found that mean wind pressure coefficients are reduced significantly due to the presence of parapets. Figure 2.1 shows the experimental results of that study in the form of contours of pressure coefficients. Increasing, the parapet's height tends to equalize the pressure over the roof surface and the effects become more pronounced with an increase on building height.

ROOF PARAPETS

ISOBARS (Cp-Contours)on ROOF

BLOCK-TYPE STRUCTURE

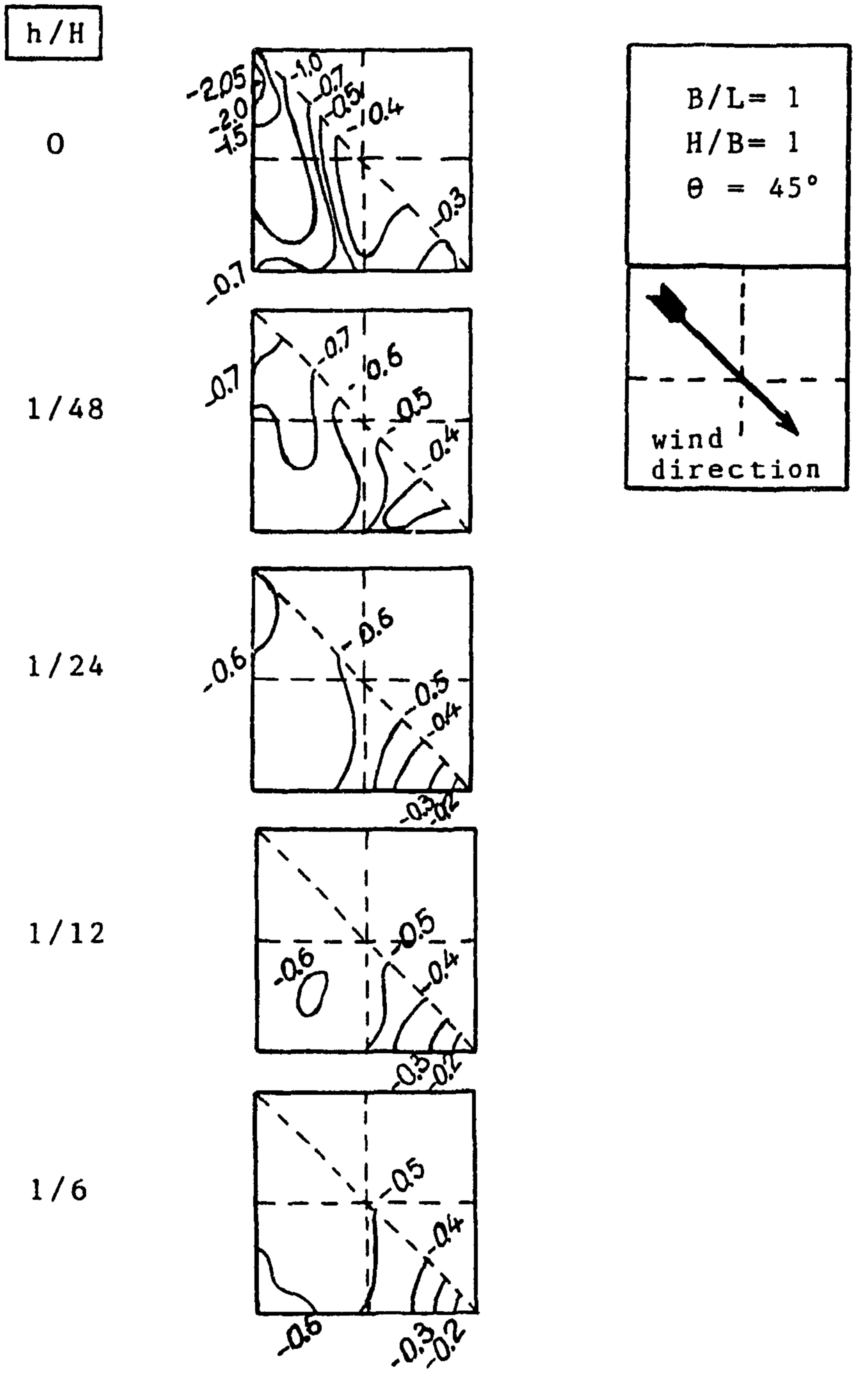


Fig. 2.1 EFFECTS OF PARAPETS ON ROOF PRESSURE DISTRIBUTION FOR CORNERING WIND (Leutheusser, 1969)

This would seem to indicate that parapets have a beneficial effect on roof wind loading. However, the critical parameter for the simulation of buildings exposed to natural wind, H/Zo (height of the building / roughness length) was neglected in this study. Thus, the above results may not be representative considering the actual turbulent flow conditions of the natural wind.

Columbus (1972) carried out various tests both in uniform and turbulent flow conditions for the same building configurations that Leutheusser (1969) tested. Only time-averaged (mean) pressures at various roof points were measured. It was found that parapets do not cause any reduction on local mean pressures in turbulent flow in contrast to the case of uniform flow.

Davenport and Surry (1974) have tested the effects of parapet on low-rise building models in a boundary layer wind tunnel. They concluded that local mean suctions become higher when parapets are added, in particular for cornering wind. Although better than the regular, the castellated parapets cause only limited load reductions.

Kramer et al. (1978) from Germany found that parapets change the pressure coefficients significantly only in the corner regions of the roof. For parapets of h/B > 0.04 in square buildings, wind pressures were reduced by more than 70 % .

Sockel and Taucher (1980) measured mean and extreme wind pressure coefficients for points close to the roof corner. They reported that, when h/H = 0.02, the extreme value suctions are reduced by as high as 50% . It was shown that by narrowing the probability density functions, the parapets also reduce the fluctuating (dynamic) pressure components.

In 1982, a more systematic approach followed by Stathopoulos (1982) gave some clear results for the effects of parapets on low-rise buildings. For a parapet height of 1.2 m, both local and area-averaged wind pressure loads in simulated open country and suburban terrains were measured. The study concluded that roof corner local suctions increase in the presence of parapets. Some recommendations, based on these experimental results, have also been made for the National Building Code of Canada.

At the University of Western Ontario, Lythe and Surry (1983) carried out an interesting study on high parapet heights with two main objectives: first, in order to determine the general distribution of wind loads on flat roofs and secondly, to enable the evaluation of the effects that parapets have on these loads. The conclusions of this work may be summarized as follows:

1) The magnitude of peak pressure coefficients in the edge regions, generally decreases with parapets

2) Low parapets on low buildings increase the magnitude of both peak and mean pressures in the corner regions. However, high parapets on low buildings and any parapets on high buildings tend to decrease these pressures.

The review of the existing knowledge was completed with the study by Stathopoulos and Baskaran (1986), which recommended that local high suctions on roof corners should be increased by 100% in the presence of low parapets (<1.0 m) and should be increased by 50% in the case of low buildings with high parapets (>1.0 m). Area-averaged loads acting on roof corners should also be increased by 20% in the presence of low parapets.

## 2.2 JUSTIFICATION OF THE PRESENT STUDY

Wind Standards and Codes of Practice give limited information regarding the effects of wind on flat roofs with parapets. The limited number of existing studies do not seem to yield consistent results.

According to Stathopoulo (1982), parapets increase the corner roof wind loads significantly. Therefore, a comparison of the local mean wind loads for corner regions of various studies has been attempted.
Figure 2.2 shows the comparison of the most critical mean pressure coefficients measured on roof corner points for various buildings and parapet configurations examined in

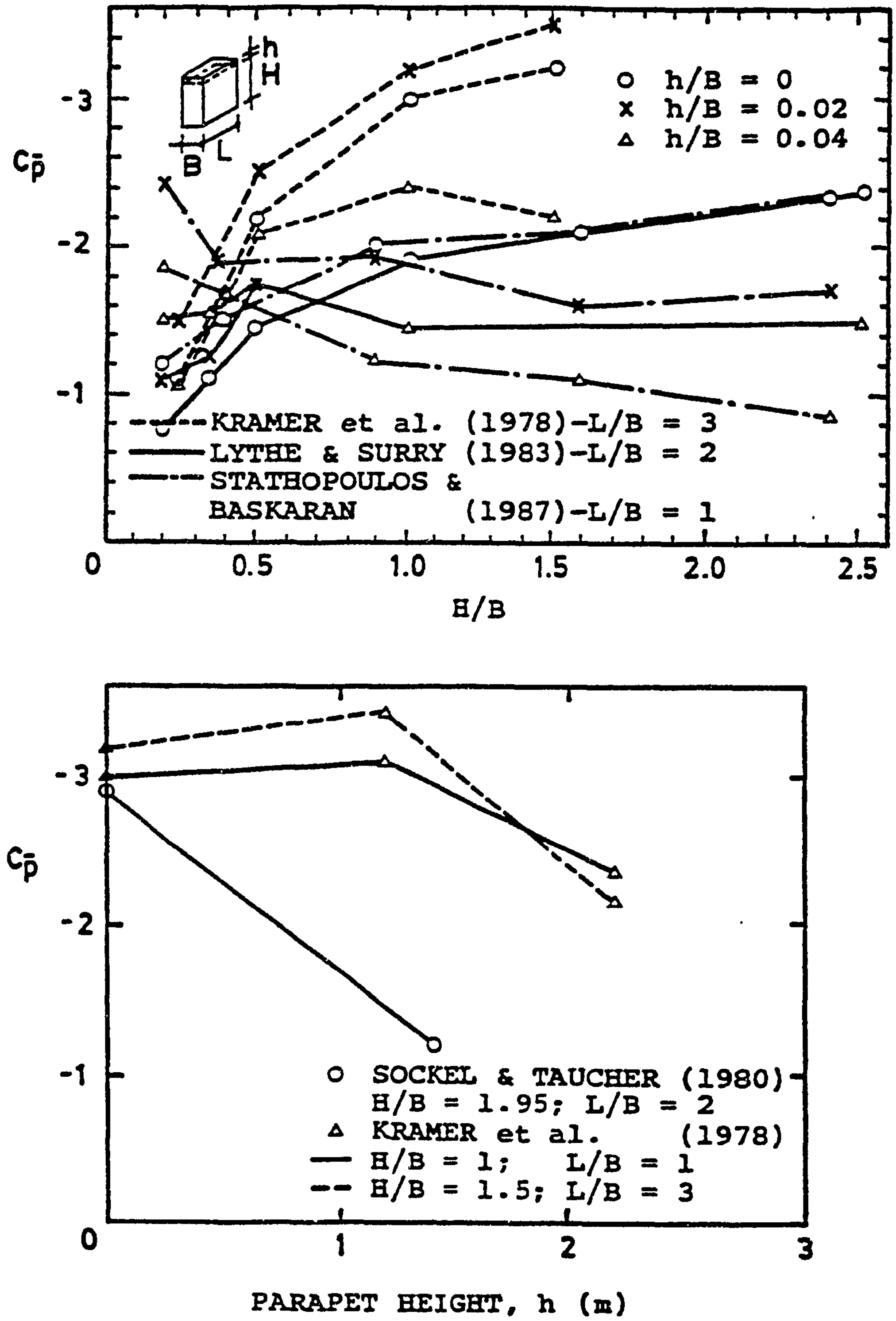


Fig. 2.2 DATA FROM PREVIOUS STUDIES ON THE EFFECT OF PARAPETS ON ROOFS

the course of four different studies. On the upper diagram, data for buildings without parapets agree well between Lythe and Surry (1983), Stathopoulos and Baskaran (1986) but they are quite different from the data obtained by Kramer et al. (1978), particularly for higher building heights.

Similarly, when introducing a low parapet, Kramer et al. (1978) measured higher suctions for all building heights, whereas Stathopoulos and Baskaran (1986) reported higher suctions (in comparison to the roof without parapets), only for lower building heights. The actual values of these coefficients are also different between these two studies, while a better agreement appears between Lythe and Surry (1983), and Stathopoulos and Baskaran (1986).

The study by Kramer et al. (1978) seems to give higher suctions in comparison with the work of Sockel and Taucher (1980) as the lower diagram of Fig. 2.2 clearly indicates.

Some investigators have suggested that the primary cause of the different magnitudes of pressure coefficients measured on flat roof edges and corners is the different location of pressure taps in the various models. This hypothesis has been examined in this thesis after a detailed experimental study about the influence of the distance of a pressure tap from the edge of a flat roof on the magnitude of pressure coefficients was carried out.

The high density of pressure taps has allowed the detailed investigation of the effect of parapets on corner wind loads for low and intermediate height buildings.

The study of Stathopoulos (1982) has measured the wind pressures for roofs having parapets 1.2m high and the study of Lythe and Surry (1983) has used roofs with parapets 1.3m and above. In practice, however, most of the flat roofs have parapets less than or around 1m. So the present study attempts to evaluate the roof corner and edge wind loads for parapets less than 1m high, too. The previous studies have tested only a few wind directions (mainly $0^\circ$ and $45^\circ$). However, in order to get the most critical pressure coefficients, additional wind directions have been tested in the present work.

# CHAPTER 3

## EXPERIMENTAL METHODOLOGY

> "Wind tunnel modelling is a complex problem and its results depend on the accuracy of the similitude criteria, and to a great extent on the researcher's experience, too."
>
> ...SCHLICHTING H.

Within the past thirty years, the field of Wind Engineering has experienced tremendous growth in research, modeling and testing activities. The wind tunnel serves as a sort of mini dress rehearsal which will reflect interaction of the structure and the wind over the life of the building. The need for defining modelling criteria and developing some level of standardization in wind tunnel model tests is becoming more important as the Building Codes and loading Standards move towards recognition of wind tunnel model test results as an alternative to prescriptive design wind loads. With respect to the nature of application, there are two types of wind tunnels: aeronautical and boundary layer.

The boundary layer wind tunnel has been utilized in the application of building aerodynamics. All the experimental work of this project was carried out in the boundary layer wind tunnel (BLWT) of the Building Aerodynamics Laboratory of the Centre for Building Studies.

## 3.1.THE CONCEPT OF A BLWT

The concept of boundary layer is originally due to Prandtl. The most comprehensive treatment of boundary layers was undertaken by Schlichting in his fundamental work (1968). The boundary layer could be described as a thin region near a solid surface, in which the effect of internal friction in a fluid cannot be neglected. In other words, the frictional effect of the solid boundaries on flow is confined to the boundary layer, in which the fluid velocity changes from zero at the solid surface, to the free flow velocity outside the boundary layer.

As shown in Figure 3.1, the boundary layer on a smooth plate could be divided mainly into two parts, the first in which the effects of the viscosity are larger (laminar boundary layer) and the main region in which the influence of the viscous force may be neglected with respect to the inertia forces. Most BLWTs simulating the wind reflect the turbulent zone in order to match the air flow characteristics with those of natural wind near the ground surface.

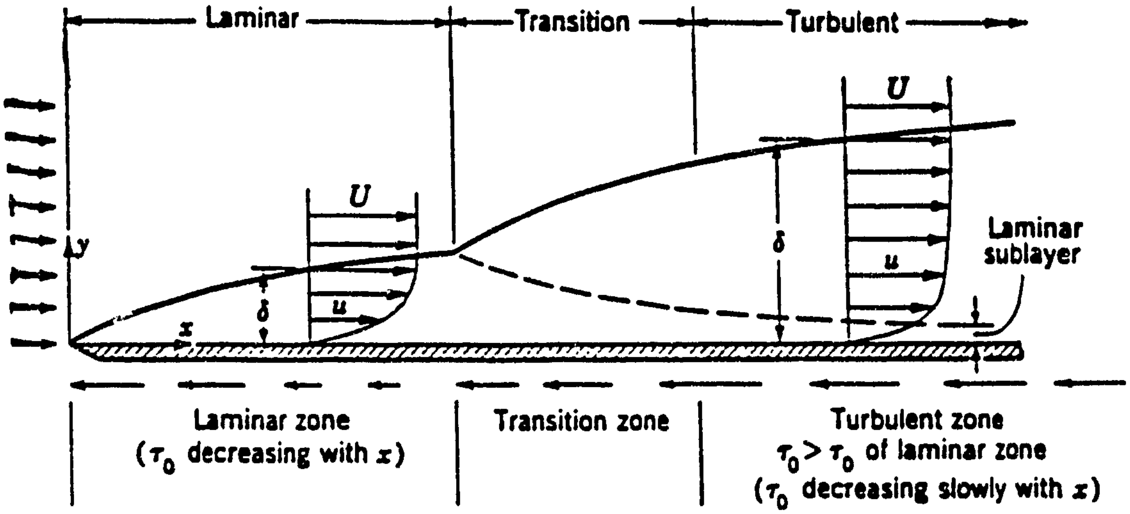


Fig. 3.1 LAMINAR AND TURBULENT BOUNDARY LAYERS ALONG A SMOOTH FLAT PLATE - VERTICAL SCALE EXAGGERATED (Daugherty, 1983)

## 3.2 WIND SIMULATION IN THE BLWT OF C.B.S.

Various methods have been used to develop the appropriate turbulence and velocity variation with height. In the BLWT of C.B.S., the boundary layer develops naturally over a rough floor. This implies that different wind tunnel floor roughnesses will develop conditions representative of different terrain exposures.

Plate 3.1. illustrates two different terrain conditions of the simulated flow. The open country terrain conditions shown in the top picture represent exposure A as per National Building Code of Canada (NBCC) or exposure C as per the American Standard (ANSI). The suburban terrain may correspond to exposure B of the NBCC or exposure B of ANSI Standard. Here, for the open country terrain, the boundary layer develops over the roughness of a carpet. For the suburban exposure, sponge sheets have been placed on the top of the carpet. The sponge sheets create the necessary roughness to yield the required turbulemce at the center of the turntable, where the model is located.

The vertical distribution of the mean velocity and the longitudinal turbulence intensity for the two simulated flow conditions are shown in Figure 3.2. As can be noted, for the same terrain roughness, the turbulence intensity

a)

b)

Plate 3.1 INSIDE VIEW OF THE TUNNEL IN SIMULATED
a) OPEN COUNTRY
b) SUBURBAN TERRAIN

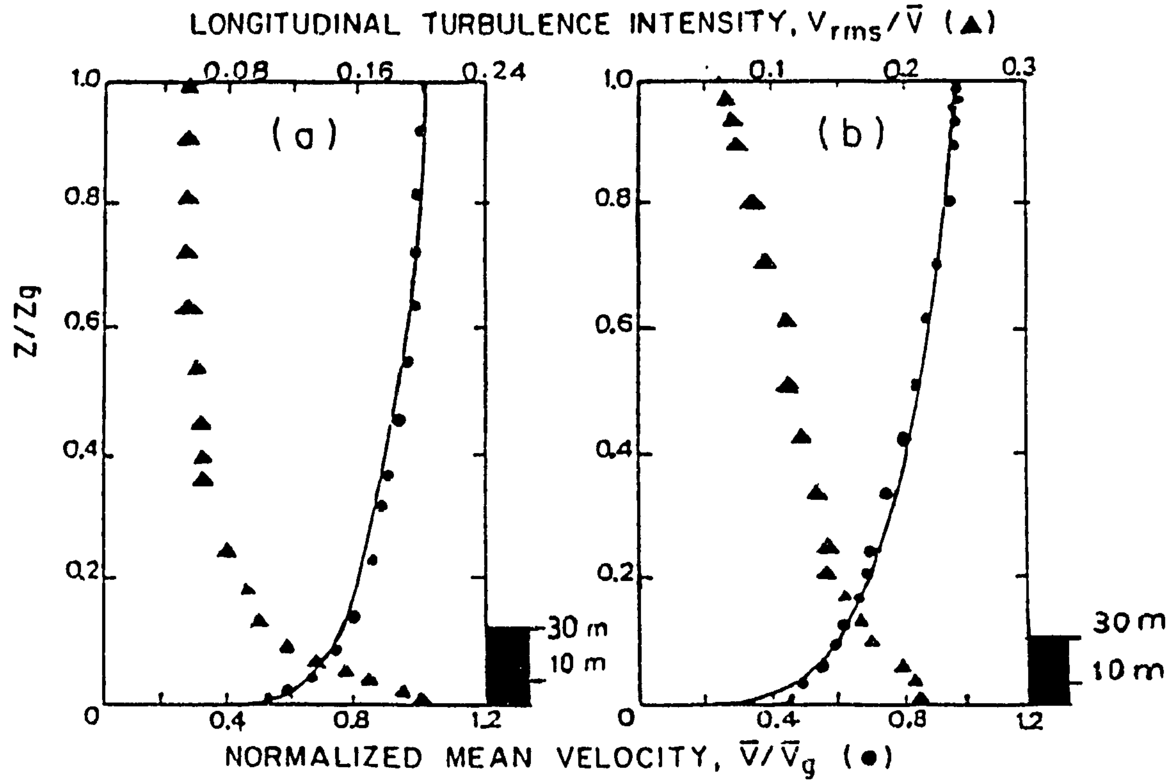


Fig. 3.2 MEAN SPEED AND TURBULENCE INTENSITY PROFILES
a) OPEN COUNTRY $\overline{V}/\overline{V}g = (Z/Zg)^{0.15}$
b) SUBURBAN $\overline{V}/\overline{V}g = (Z/Zg)^{0.21}$
SIMULATED TERRAIN EXPOSURE

decreases with the increase of height above ground, and for the same height, the turbulence intensity increases with the increase of terrain roughness.

By using a power law equation of the form

$$\bar{V}/\bar{V}g = (Z/Zg)^{\alpha} \qquad 3.1$$

the best fitted velocity profiles exponent may be estimated as 0.15 and 0.21 for the open country and suburban terrain conditions respectively. Experimental values are also fitted by using a logarithmic law equation of the form:

$$\bar{V}/\bar{V}g = 0.4\ Cg\ \ln(Z/Zo) \qquad 3.2$$

and the various parameters including Cg and Zo are provided in Table 3.1.

The simulation of the flow will be more complete, and a geometrical scale for the model may be assigned when the spectral curve of longitudinal turbulence is established. The most appropriate parameters of the wind tunnel flow regime are given in Table 3.1, along with some full scale values which are taken from references (Counihan, 1974 and Davenport, 1963). Based on these data together with the spectrum of the longitudinal turbulence component, a geometric scale of about 1:400 has been established. The exact determination of geometric scale is not absolutely

|  | FULL SCALE |  | WIND TUNNEL |  |
|---|---|---|---|---|
|  | OPEN COUNTRY | SUBURBAN | OPEN COUNTRY | SUBURBAN |
| ZG (m) | 220-270 | 300-400 | 0.60 | 0.70 |
| Zo (m) | 0.001-0.20 | 0.2-1.2 | 0.0001 | 0.0045 |
| $\alpha$ | 0.16 | 0.24 | 0.15 | 0.21 |
| Cg | 0.042 | 0.044 | 0.042 | 0.044 |

Table 3.1 PARAMETERS FOR FULL SCALE AND SIMULATED FLOW CONDITIONS

necessary as has been demonstrated in the past. For example, for low buildings, some small relaxation of the scale (up to a factor 2) is permissible for both local and area-averaged loads. This yields errors of the order of 10 % or less in the estimations of loads (Davenport, 1974 and Stathopoulos and Surry, 1983).

More information about the simulation characteristics and the design and fabrication of the C.B.S.'s wind tunnel can be found in Stathopoulos (1984).

## 3.3 VARIOUS CONFIGURATIONS TESTED

The basic model used in the present study represents a flat-roof square building 61m x 61m, in plan. The model is made of plexiglass and it has been tested with and without parapets, in simulated open country and suburban terrain exposures. Plates 3.2 and 3.3 show the model in open country and suburban exposures respectively. Both conventional local load and area-averaged measurements have been carried out. The pneumatic averaging technique (Surry and Stathopoulos, 1983) has been used for the measurement of area-averaged pressures. The model was equipped with the highest possible density of pressure taps arranged at a minimum distance from the edge of the roof.

Figure 3.3 shows a sketch of the assembly which was constructed as a separate unit (module) and attached to the roof. The outer component of the assembly, which

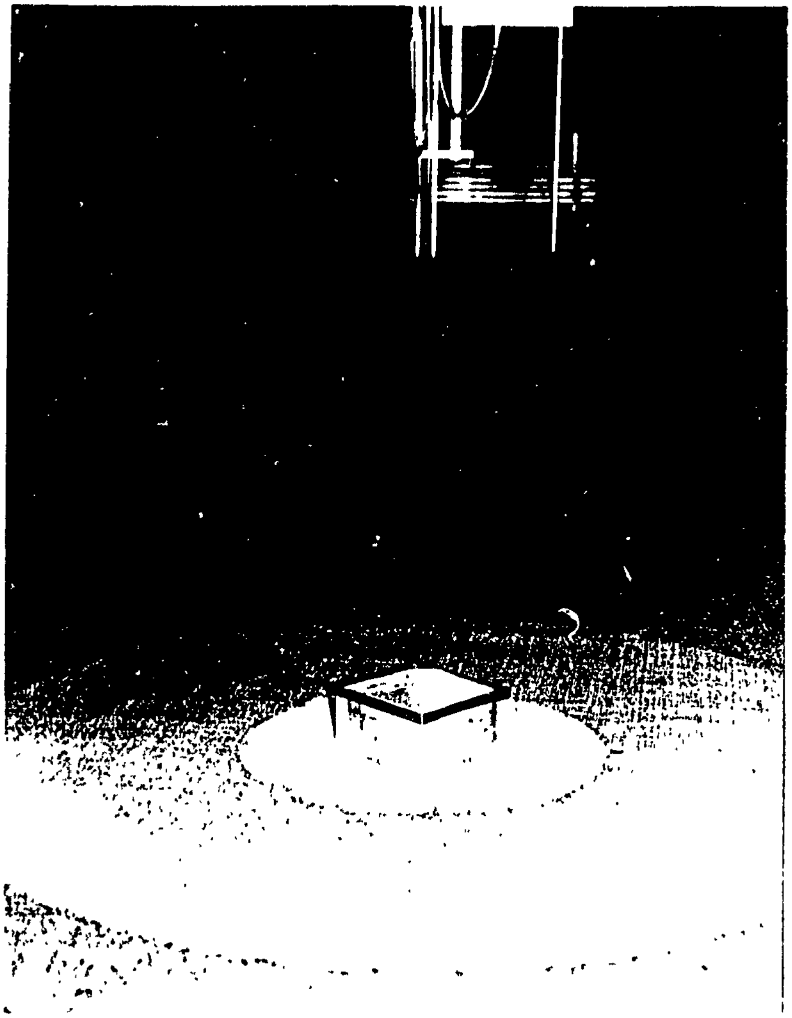


Plate 3.2 BUILDING MODEL WITH PARAPET IN OPEN COUNTRY TERRAIN

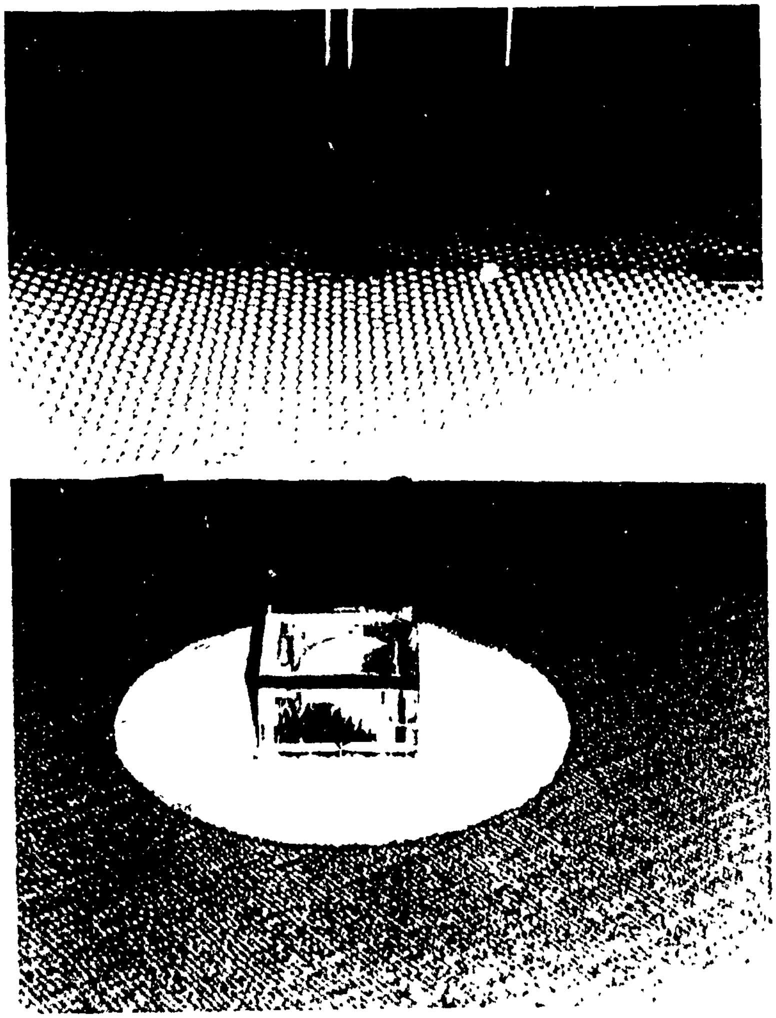
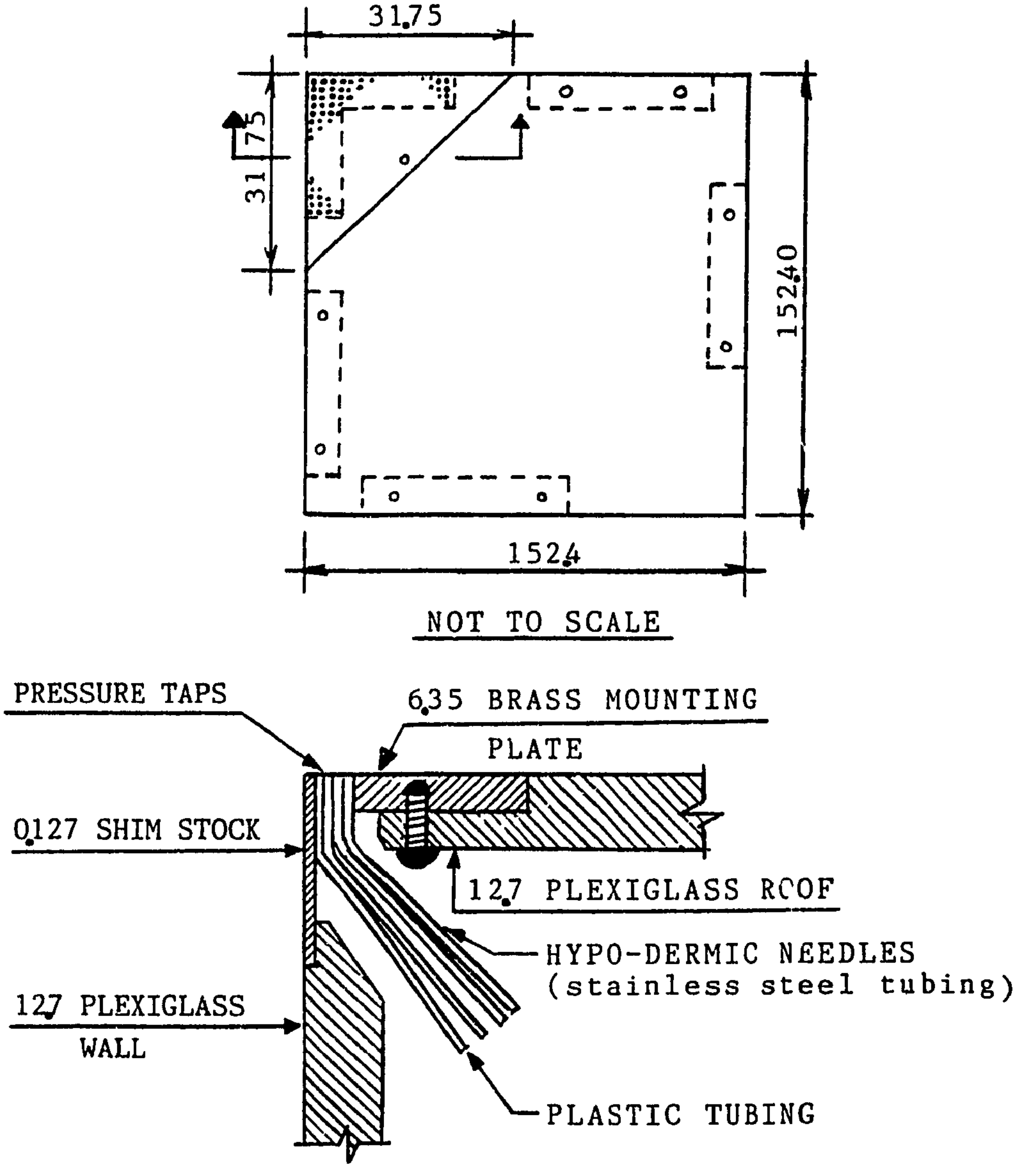


Plate 3.3 BUILDING MODEL WITH PARAPET IN SUBURBAN TERRAIN



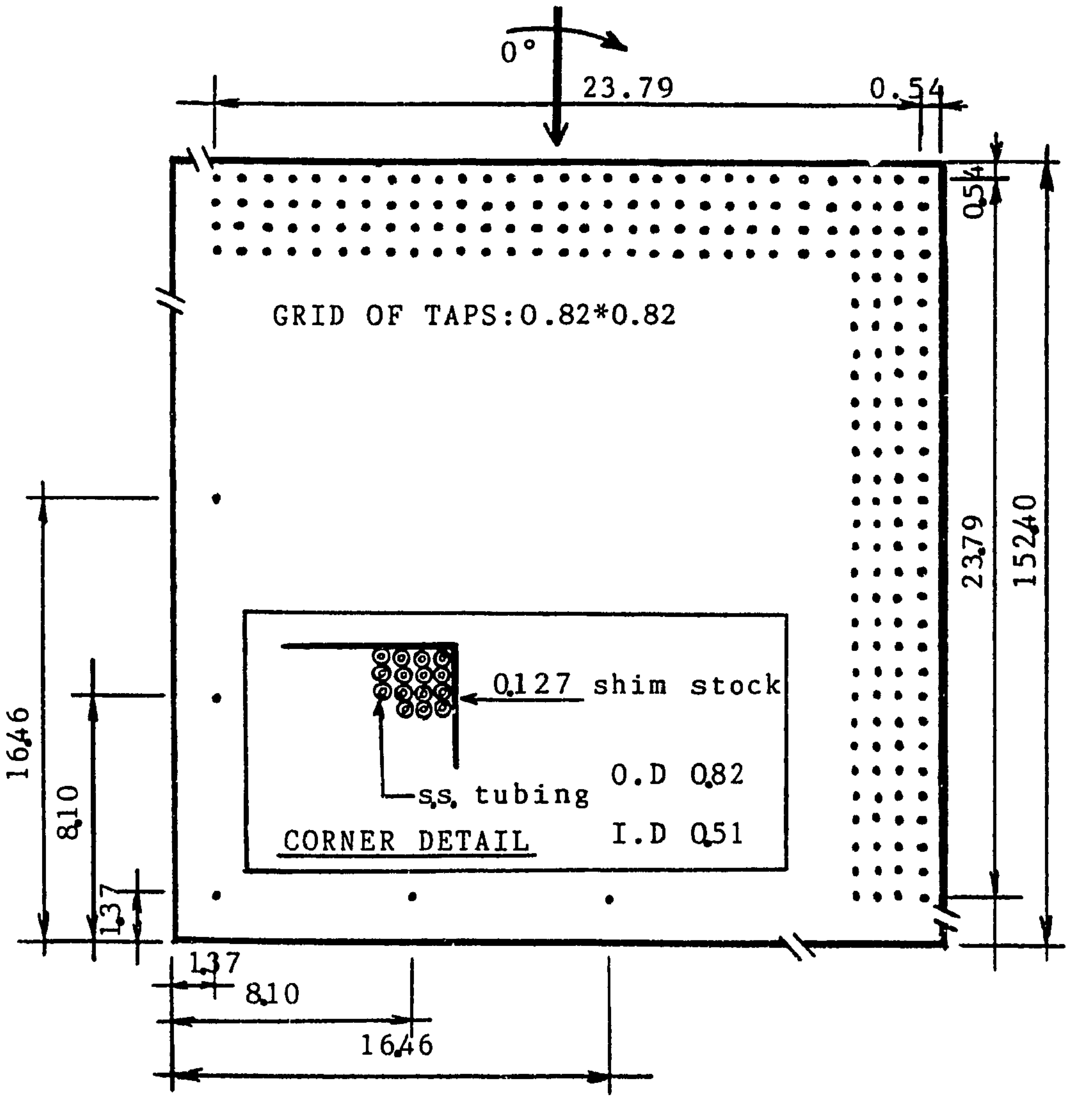
dimensions in mm

**Fig. 3.3 DETAILED SKETCH OF THE PRESSURE TAP ASSEMBLY**

forms also part of the exterior wall of the model, was made of 0.13mm hard brass shimstock, to which four rows of 21 gauge 38mm long hypodermic needles were soft-soldered together with a 6.4mm thick brass plate in order to provide rigidity and also a means to fasten the assembly to the roof of the model. A suitable opening was machined into the corner of the building to allow inserting the pressure tap assembly - a total of 224 needles - and to provide space for the plastic tubing connecting the individual pressure taps to the SETRA - 237 pressure transducers via scanivalves. The sides of the model were attached to the roof with aluminum angles and screws. The dimensions of the roof and the exact location and dimensions of the pressure taps appear in Figure 3.4.

The model was tested at 25.4mm and 76.2mm (10m and 30m, full scale) heights which vary the height-width ratio H/W from 0.167 to 0.5.

Five additional taps drilled at the exact symmetric (wrt roof diagonal) position of five selected taps of the assembly. Pressure data from these additional points for symmetric wind directions can thus be compared with the results obtained from the respective taps of the assembly to detect any possible error due to the interaction between the wind flow and the adjacent taps. Despite the close proximity of taps of the assembly among them and from the edge of the roof, comparisons of such data have indicated that this interaction effect is negligible.



dimensions in mm

Fig. 3.4 PRESSURE TAP LOCATION

Five parapet heights, namely 0.0; 0.50; 1.0; 1.5 and 3.0m have been generally used. The high parapet of 3m has been included in order to enable the study of the trends of the data regarding the effect of the parapets on roof suctions in detail. These parapets may also represent cases of buildings under construction or partly damaged. An additional parapet 0.3m high has also been tested partly for the assessment of corner wind loads for very low parapets.

Based on considerations of existing Standards and Building Codes of Practice (ANSI and NBCC 1990), a number of different tributary areas have been selected on the roof for measurement of area-averaged loads. The location and the size of these areas are shown in Figure 3.5.

The two buildings have been tested for several wind directions. The symmetry of the roof and the symmetric locations of the pressure taps have also been considered when determining the necessary wind directions. A summarized, schematic diagram for the various configutations tested is presented in Figure 3.6.

## 3.4. DATA ACQUISITION AND INSTRUMENTATION

All pressures were measured by using SETRA 237 dynamic pressure transducers (0.1 psid range) placed in a scanivalve. Pressure taps on the roof were connected to the scanivalve through a short plastic tubing with internal diameter of 1.6mm as shown in Plate 3.4.

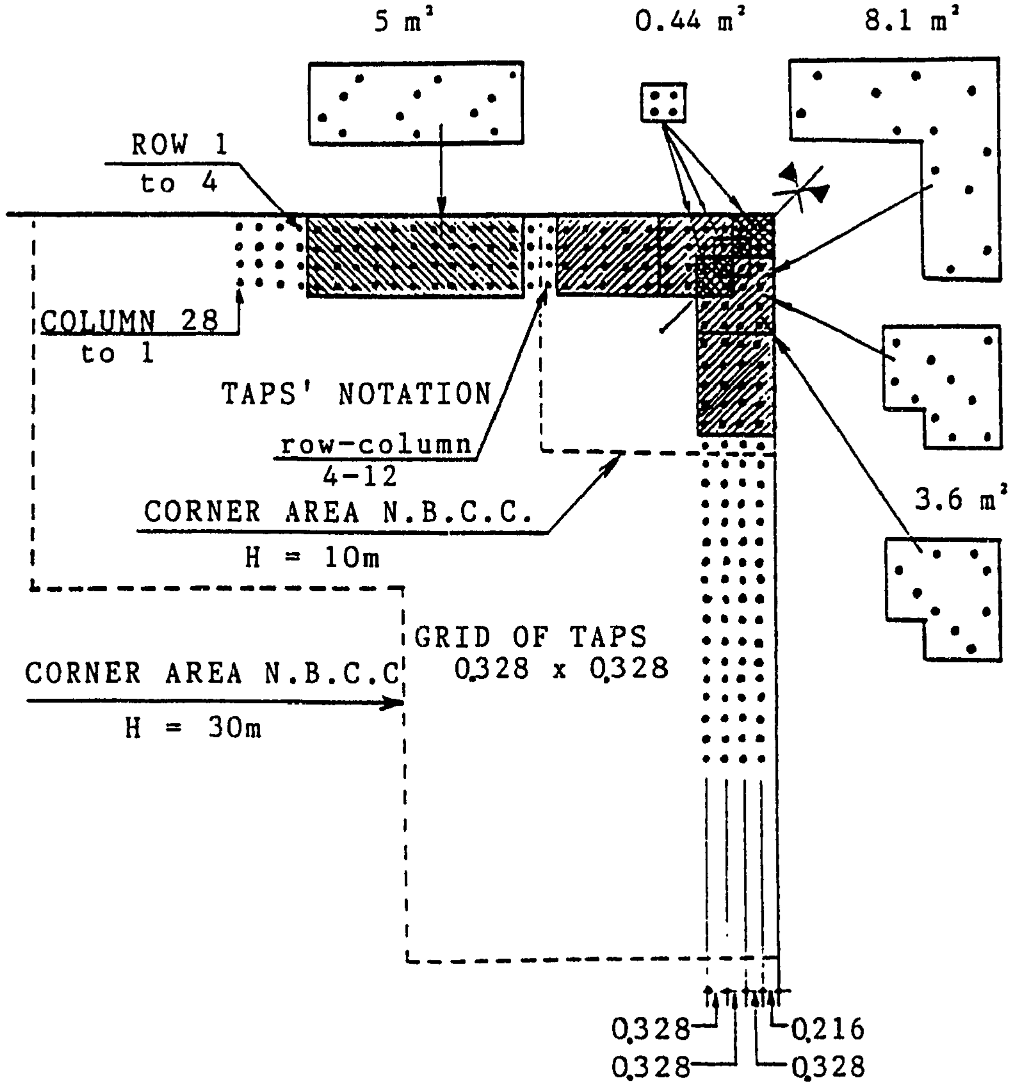


Fig. 3.5 TRIBUTARY AREAS CONSIDERED FOR THE MEASUREMENT OF AREA-AVERAGED LOADS

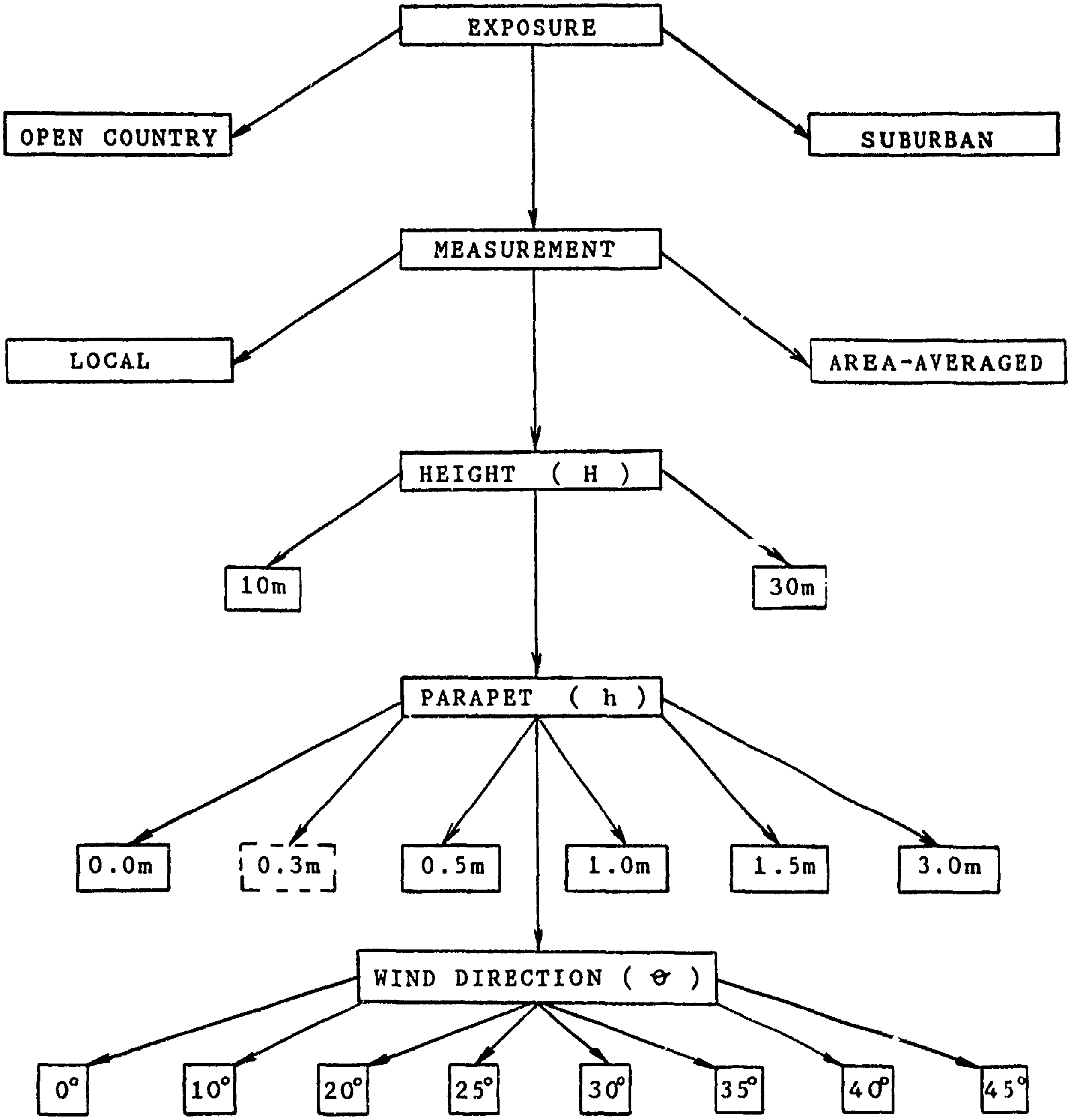


Fig. 3.6 VARIOUS CONFIGURATIONS TESTED

Plate 3.4 BUILDING MODEL WITH PLASTIC TUBING AND SCANIVALVE

The pressure measuring system in use at the Center for Building Studies provides a frequency response virtually flat to about 100 Hz, with negligible attenuation or distortion. Higher frequencies suffer increasing attenuation, although some response is obtained for signals of several hundred Hertz.

The procedure followed for the local load and area-averaged pressure measurements is shown diagrammatically in Fig. 3.7. A sampling rate of 500 samples per second over a sampling time of 15 seconds has been used for each measurement.

## 3.5. DEFINITION OF PRESSURE COEFFICIENTS

All pressures in the wind tunnel were measured in a coefficient form with respect to the stable, mean dynamic velocity pressure $1/2\rho \bar{V}^2$ above the boundary layer for a wind speed of approximately 12 m/s. This height corresponds to the gradient height at which surface frictional effects cease to be significant. By using the velocity profiles (Figure 3.2) such measured pressure coefficients could be referenced to any height within the boundary layer. Most Building Codes of practice and Wind Standards provide pressure coefficients with respect to roof height level. Therefore, the coefficients discussed in the present work have been determined similarly as follows:

$C\hat{p} = \hat{P}/qH$ $C\check{p} = \check{P}/qH$

$C\bar{p} = \bar{P}/qH$ $C\bar{\bar{p}} = \bar{\bar{P}}/qH$

in which,

$\hat{P}$: the maximum instantaneous pressure measured over the sampling period

$\check{P}$: the minimum instantaneous pressure measured over the sampling period

$\bar{P}$: the time - averaged mean pressure

$\bar{\bar{P}}$: the root mean square pressure

$qH = 1/2\,\rho\,\bar{V}^2$, the dynamic pressure associated with the mean velocity at roof height and $\rho$ is the density of air.

All pressures are differential pressures with respect to the static pressure at the gradient height. The height correction factors ( qG / qH ) are given in Table 3.2.

A pictorial representation of typical pressure coefficients is given in Figure 3.8. The mean pressure gives an indication of the static wind load that can be expected. The $C\hat{p}$ or $C\check{p}$, which is the measure of storm pressure or the maximum suction for the roof is mostly needed for the design of cladding elements. The rms value is a measure of fluctuations in the pressure signal. Larger deviations from the mean value will give a higher rms value. All pressure coefficients have been recorded and their trends are analyzed and discussed in the next chapter.

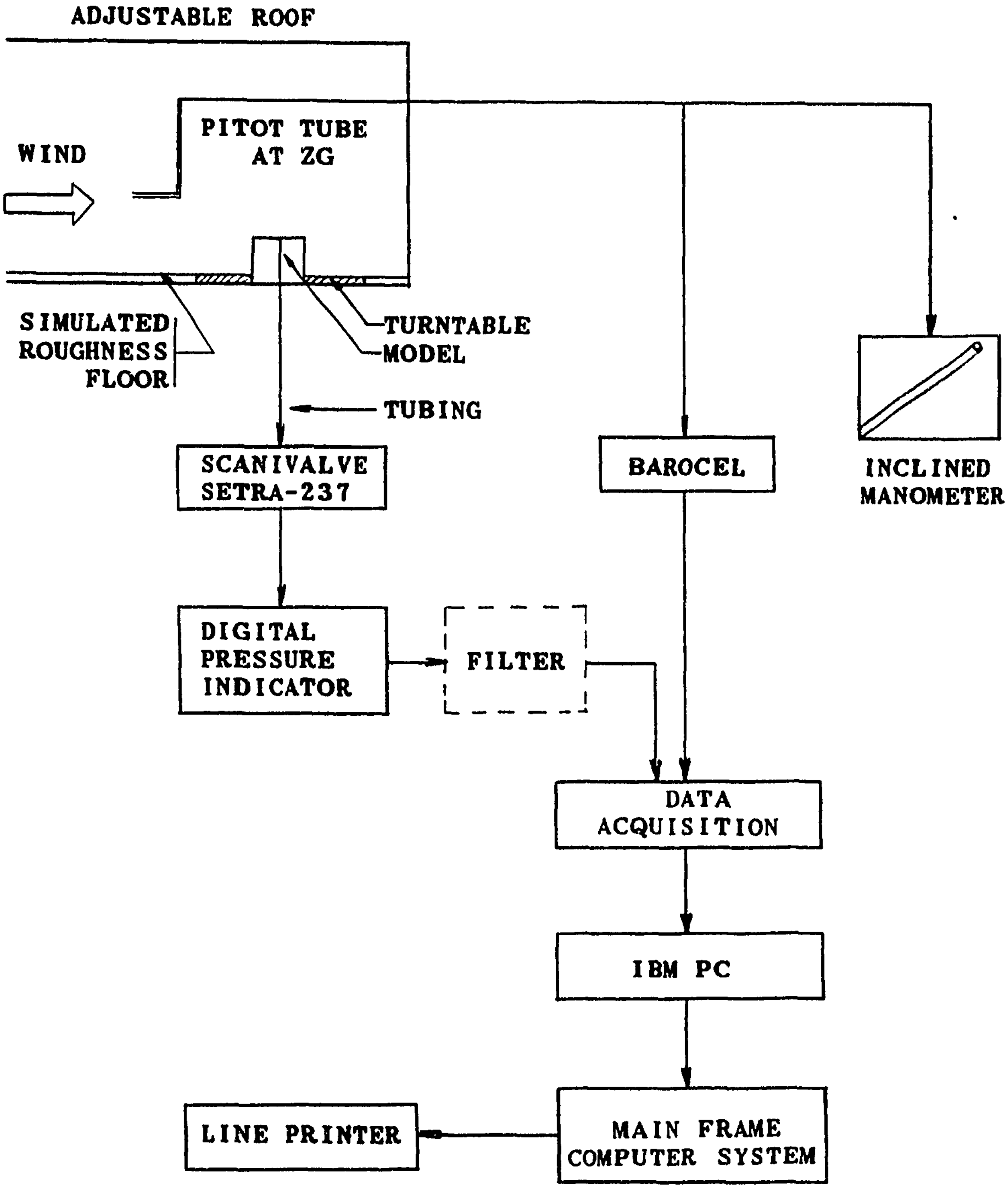


Fig. 3.7 EXPERIMENTAL SETUP FOR LOCAL AND AREA-AVERAGED PRESSURE MEASUREMENTS

| TERRAIN | BUILDING HEIGHT H(m) | HEIGHT FACTOR |
|---|---|---|
| OPEN COUNTRY | 10 | 2.9 |
|  | 30 | 2.02 |
| SUBURBAN | 10 | 3.77 |
|  | 30 | 2.38 |

Table 3.2 FACTORS RELATING DYNAMIC PRESSURE AT ROOF HEIGHT TO PRESSURE AT GRADIENT HEIGHT

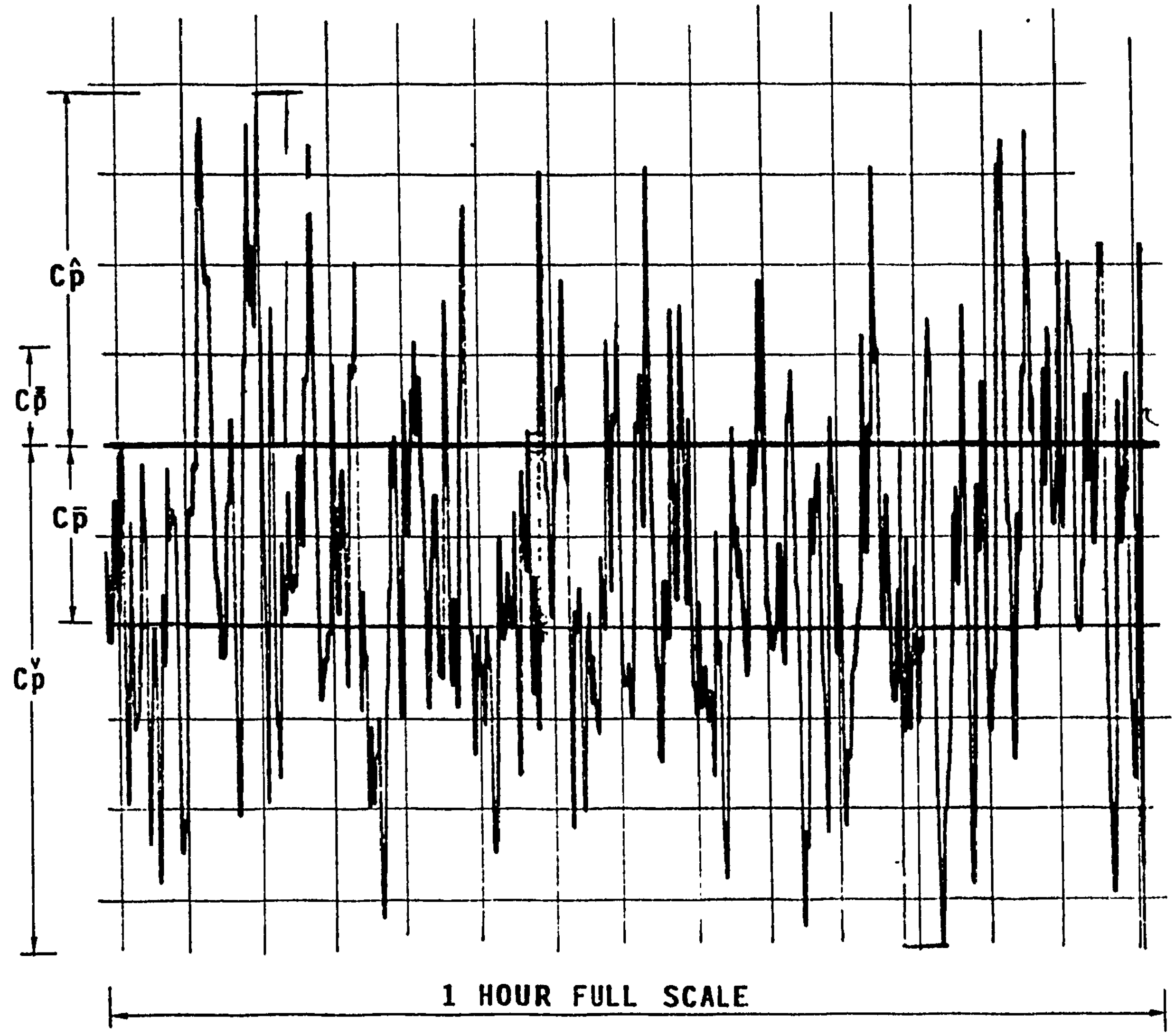


Fig. 3.8 DEFINITION OF STATISTICS OF PRESSURE COEFFICIENTS

# CHAPTER 4

# RESULTS AND DISCUSSION

> "There has been some controversery in wind engineering about the magnitude of pressure coefficients measured on flat roof edges and corners."
>
> ...T.Stathopoulos

## 4.1 GENERAL

The experimental results are presented in this chapter. Some comparisons of the present results with those of previous works are also made for validation purposes. Most Wind Standards and Building Codes of Practice divide the building roof into three regions:

- moderately loaded interior region
- heavily loaded edge region
- the maximum loaded corner region.

Wind Standards provide different loadings for each of these regions.

As described in the previous chapter, the model used in this study is a special flat roof with an assembly of 224 taps distributed on one corner and along its concurrent edges. Therefore, the results and discussion will refer just to the area covered by taps, i.e. the corner and partly the edge region. The high density of pressure taps has allowed the detailed investigation of the effect of the distance of taps from the edge of the roof on the pressure coefficient measured.

In order to better understand the effect of parapets on roof wind loading, the experimental results of this study are organized and presented in the following fashion.

The overall effect of parapet on roof wind loading is discussed in the first section.

The second section refers to the reduction/increase of wind loads on the roof edges due to parapets.

Finally, the wind induced roof corner loads are discussed and much attention is paid in these corners, where most of the roof failures occur in practice.

Generally, the effect of parapet on local loads acting on building roofs in open country and suburban exposure is disussed first. Then, the area-average wind loads measured in open country terrain are presented. In most cases, both mean and peak pressure coefficient values are analyzed.

## 4.2 PREVIOUS DATA AND PRESENT STUDY RESULTS

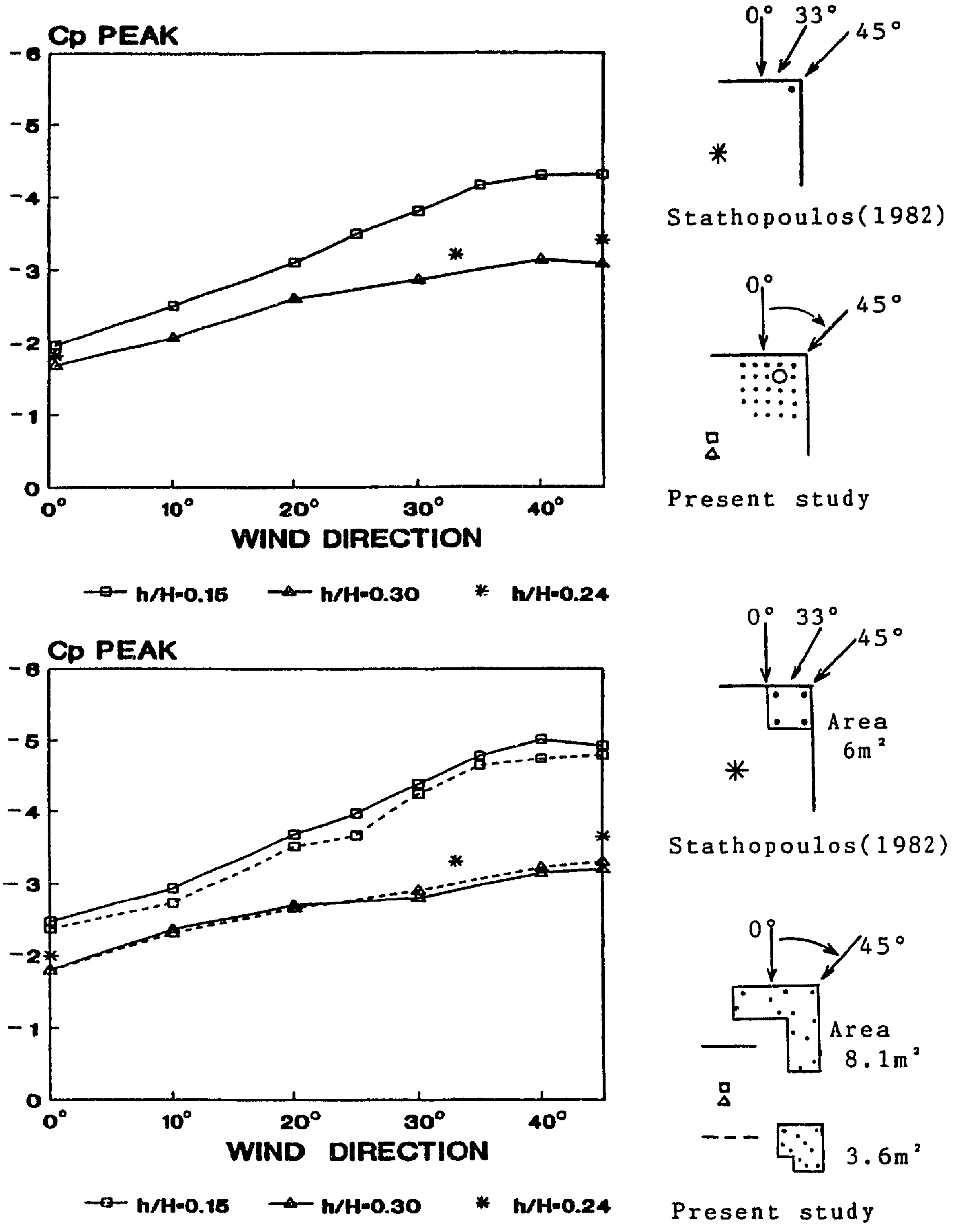
In Figure 4.1, the data of the present study are compared with the experimental results of Stathopoulos (1982). The top half of the figure presents a comparison of local peak pressure coefficients for a roof corner point measured in the open country exposure. The bottom half of the figure presents the area averaged peak pressure coefficients for the same terrain exposure. The ratio h/H parapet height over building height has been used to eliminate the differences of the parapet height (previous study has tested only a 1.2m parapet) and building height (H=12m was tested in the previous study).
Generally, the agreement between the two studies is quite satisfactory. Some variations may be attributed to the difference in the model geometry and in taps location.

Figure 4.2 compares the data of the present study with the experimental results of Kind and Wardlaw (1980). Both mean and peak pressure coefficient contours for h/H=0.05 (present study) and h/H=0.054 (previous study) are presented. The mean pressure results were similar in terms of magnitude for both studies, but the peak suctions were somewhat different. The difference in Cp peak values could result from the peaks' randomness. In both studies measurement results are based on the acquisition of single peaks and some differences are expected in the estimation of peak pressures.

The peak pressure coefficients are random and the theory of Extreme Value Distribution (E.V.D.) could be used for the estimation of peaks at a particular realiability level. However, this process is time consuming and frequently laboratories rely on single peaks acquired from a sufficiently long record.

In order to assure a small possibility of errors expected in the peak pressure coefficients values a high sampling rate of 500 samples per second for a period of 15 seconds was used. Sampling rate has a more significant effect on fluctuating peaks.

Figure 4.3 shows repeatability results of the experimental work. The two sets of mean pressure coefficient data compared have been measured in a similar set-up on two occasions, 25 days apart. The agreement noticed is typical for other cases tested and it is quite encouraging.



**Present study h/H=0.15 and h/H=0.30**
**Stathopoulos (1982) h/H=0.24**

Fig. 4.1 COMPARISON OF LOCAL PEAK NEGATIVE AND AREA-AVERAGED PRESSURE COEFFICIENTS ON ROOF CORNER: PRESENT STUDY AND STATHOPOULOS (1982)

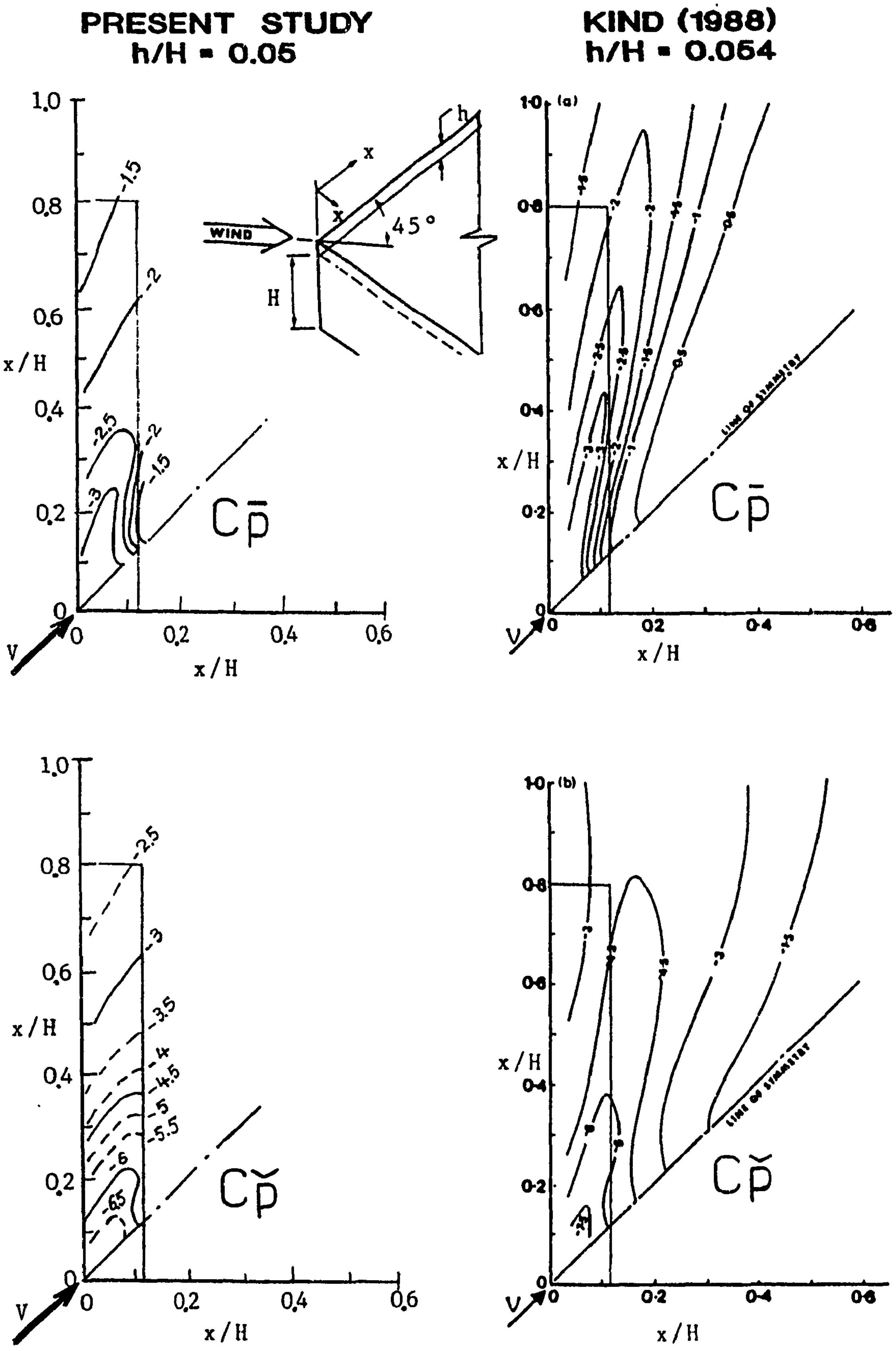


Fig. 4.2 COMPARISON OF MEAN AND PEAK NEGATIVE PRESSURE COEFFICIENT CONTOURS

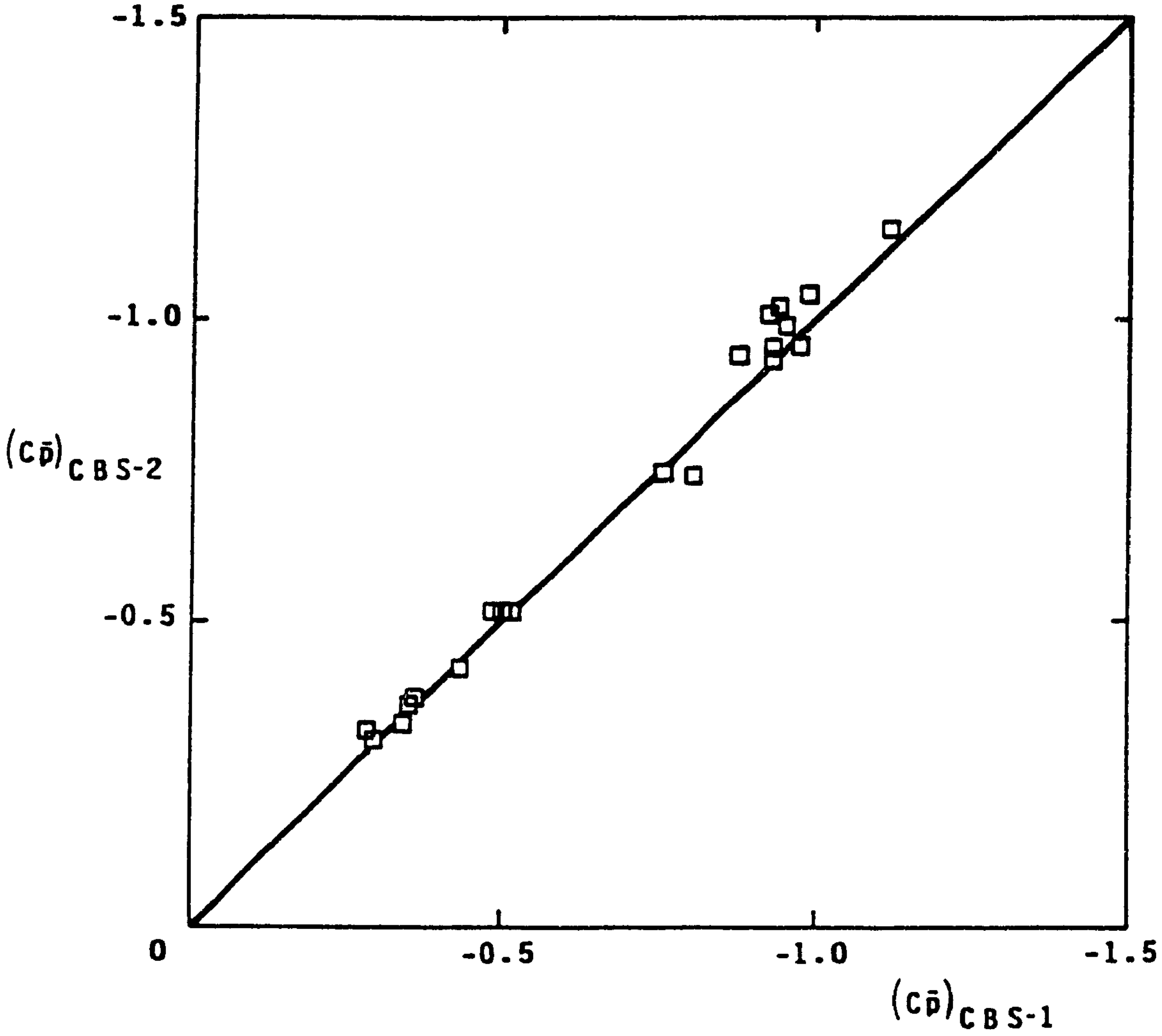


Fig. 4.3 REPEATABILITY OF MEAN PRESSURE COEFFICIENTS

## 4.3 OVERALL EFFECT OF PARAPETS ON ROOF WIND LOADING

Contours of mean and peak pressure coefficients for 45° wind direction are presented in Figures 4.4 and 4.5 for H=10m and H=30m respectively. Graphs have been arranged according to parapet height for the two building heights tested and they refer to the open country exposure results. The interval between two consecutive contour lines is 0.5. Graphs show the highest magnitude and the position of the tap in which this occurs, too. The notation of taps contains two numbers, the first one representing the row position, while the second one the column's - see Fig. 3.5. So, the exact location of any desired tap could be easily calculated, using the given dimensions in the same figure.
The highest magnitude of pressure coefficients is measured in the case of 1.0m parapet height for the low building (H=10m) and for 0.5m parapet height in the case of intermediate height building (H=30m).

Similar patterns of contours are presented in Appendix 1 for the open country terrain exposure and 30° wind direction. In this case, the comparison among graphs shows the same trend of variation of pressure coefficients with parapet height like in the case of 45° wind direction.

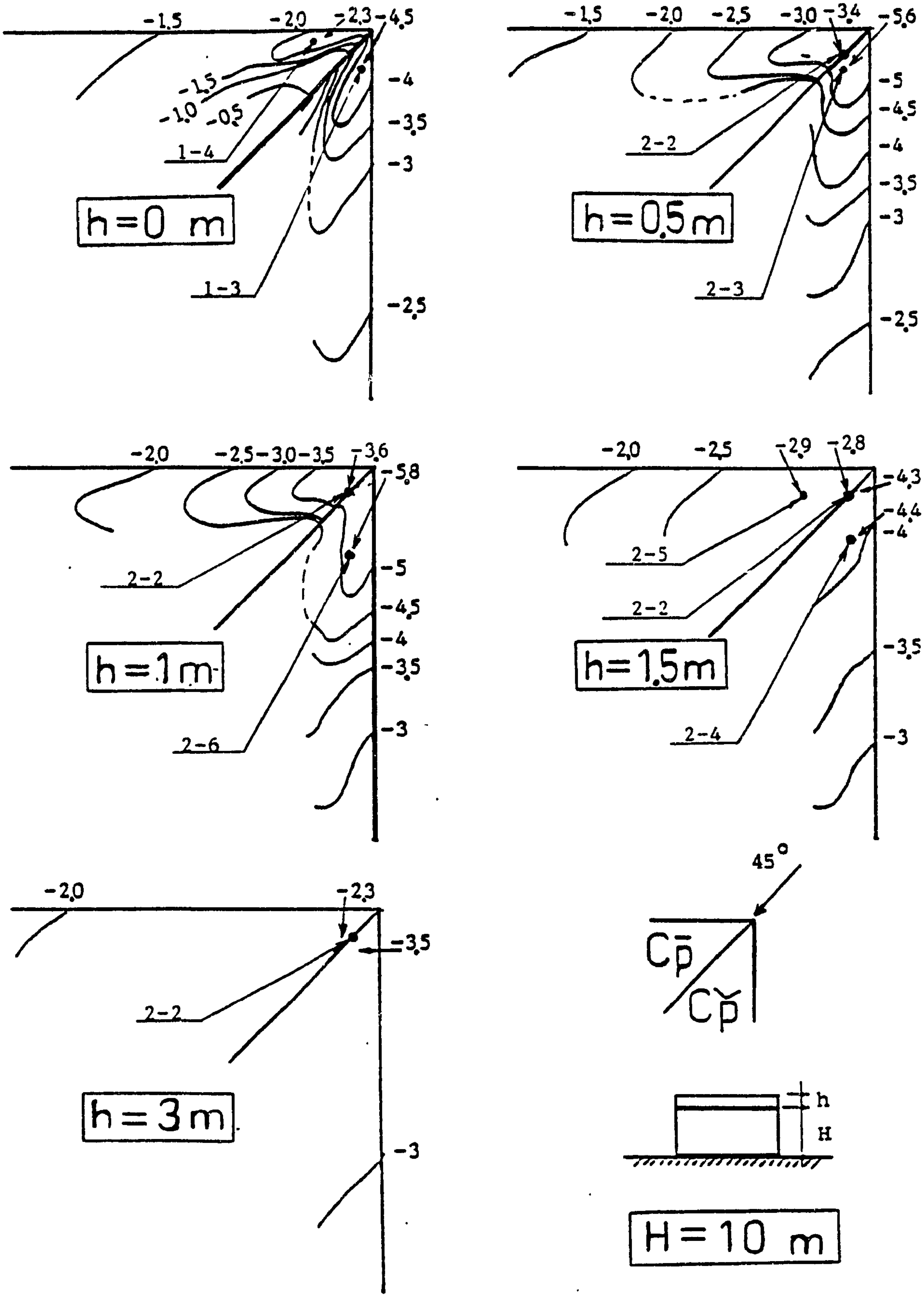


Fig. 4.4 CONTOURS OF MEAN AND PEAK PRESSURE COEFFICIENTS FOR H=10m (OPEN COUNTRY EXPOSURE)

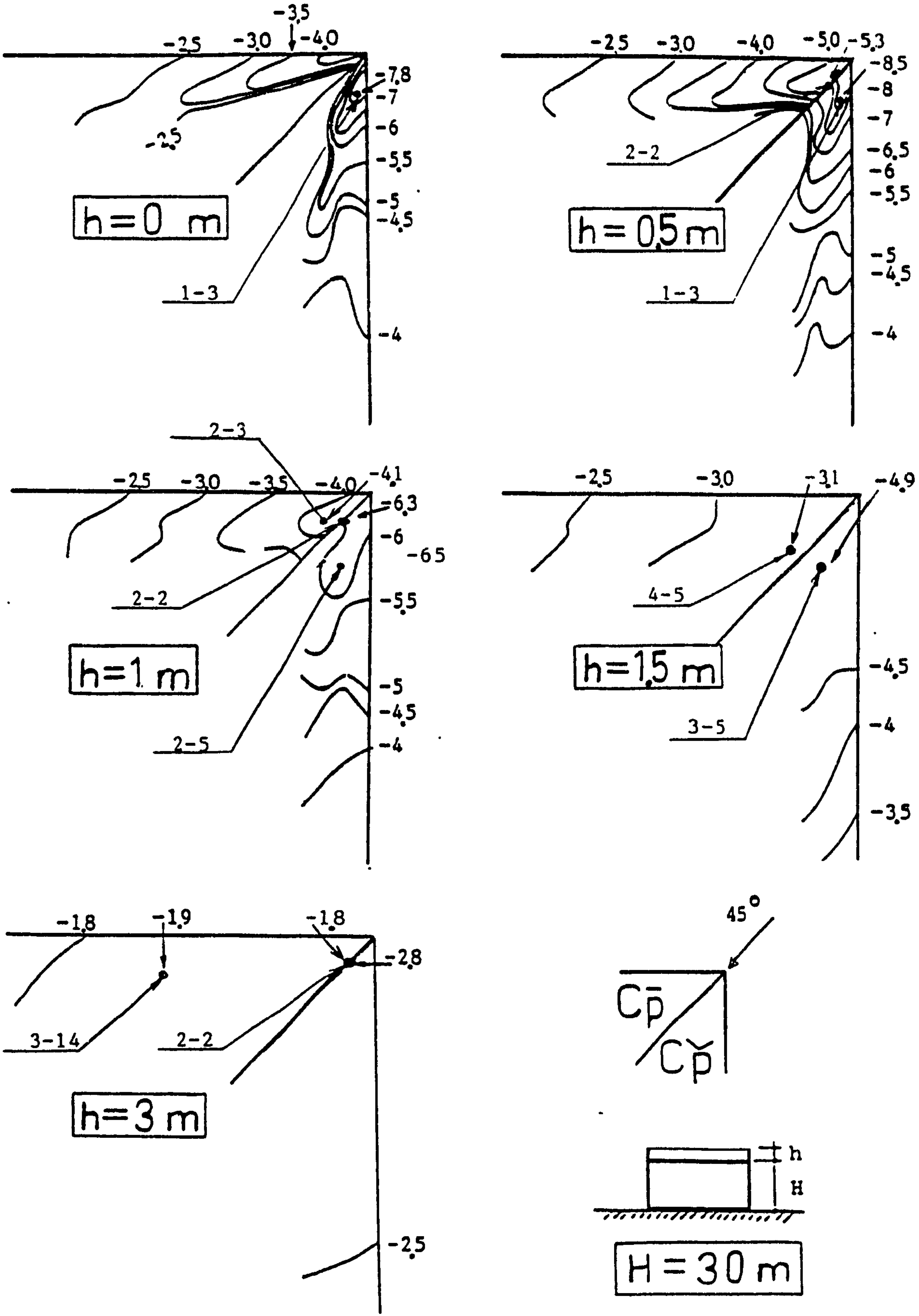


Fig. 4.5 CONTOURS OF MEAN AND PEAK PRESSURE COEFFICIENTS FOR H=30m (OPEN COUNTRY EXPOSURE)

Data for both cases of wind direction indicate that pressure coefficients get higher values for $45^\circ$ wind direction when a parapet is attached around the roof. The effect of azimuth on mean and peak pressure coefficients will be discussed in detail in section 4.5. For each pressure tap on the roof, both mean and peak pressure coefficients have been collected for eight wind directions. The most critical among the eight values was selected as the worst azimuth case.

The countours of the most critical mean and peak pressure coefficients for all parapet heights and both building heights are shown in Figures 4.6 and 4.7. In general, data indicate that parapets of 0.5m and 1.0m height increase the magnitude of mean and peak pressure coefficients in the case of low buildings (H=10m) whereas only the 0.5m parapet has the same effect on intermediate buildings (H=30m). All other parapet heights reduce both mean and peak wind loadings and their effect is more pronounced for higher parapets.

Comparing the reduction between the mean and peak, the latter seems to benefit more for all parapet heights. In the case of low parapets, the suction peak occurs very close to the roof edge. As the parapet height increases, the suction peak becomes lower and broader, and also moves inwards from the roof edge. Thus, the lack of pressure taps very close to the roof edge could generate a false trend for suction versus parapet height and

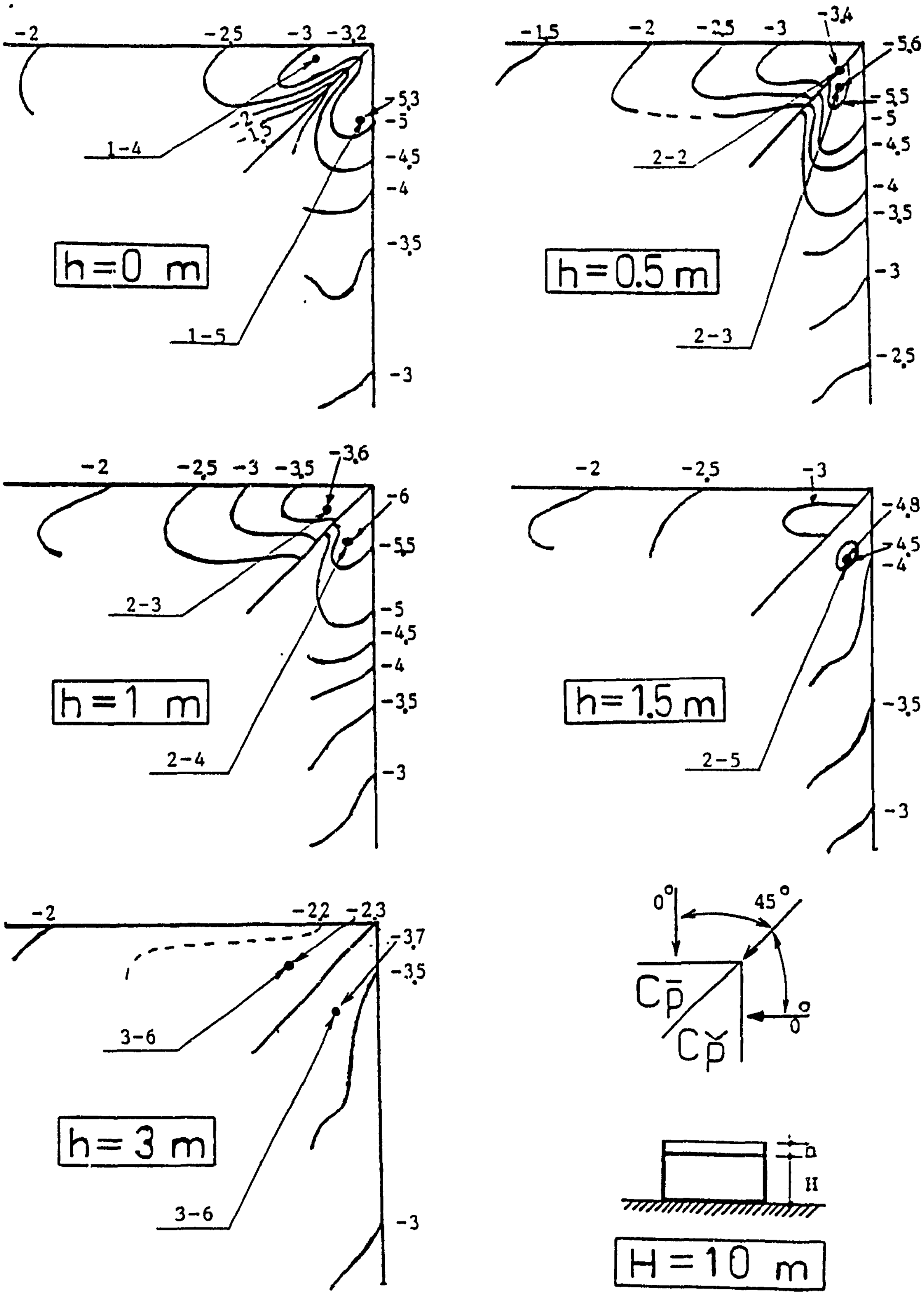


Fig. 4.6 CONTOURS OF MOST CRITICAL MEAN AND PEAK PRESSURE COEFFICIENTS FOR H=10m

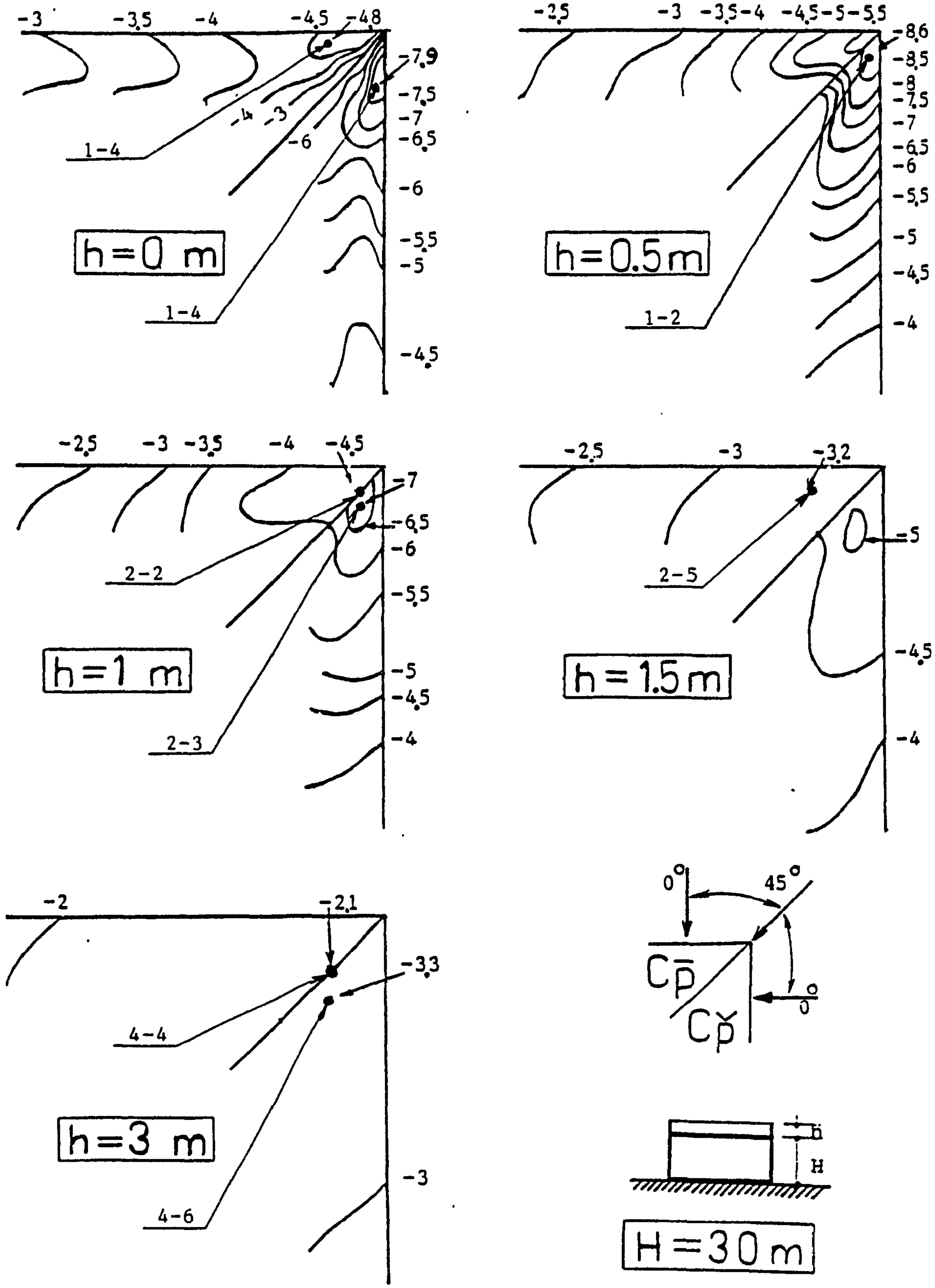


Fig. 4.7 CONTOURS OF MOST CRITICAL MEAN AND PEAK PRESSURE COEFFICIENTS FOR H=30m

the very severe suctions which occur at the corner area in the case of buildings without parapets may remain undetected. The influence of tap location is also higher for oblique wind directions. This was expected because of the conical vortex flow developed over the roof for these wind directions. The diameter of the vortex increases and its strength decreases with the distance from the corner.

An analysis of the data indicates that the influence of tap location on the pressure coefficients measured is clearly higher for buildings without parapets and decreases with the increases in the parapet height.

The influence of building height on the effect of a parapet on the wind pressures acting on the roof shows a clear trend: the reduction of suctions is higher for intermediate buildings than for low buildings (as will also be shown in Figure 4.15).

The physical mechanism behind the general reduction of pressures due to parapets on the roof is not very clear. However, this reduction may be due to the fact that parapets tend to lift the shear layer or turbulence associated vortices away from the roof surface.

## 4.4 WIND LOADS ON ROOF EDGES WITH PARAPETS

Wind loading is more sensitive closer to the edge from which the flow separates. Information about loads on roof edges is available in the literature. However, information about the changes in the loading of roof edges due to parapets is very seldom to find.

The National Building Code of Canada (1990) does not provide wind load specifications for buildings of intermediate height; nevertheless, for H>20m , most designers use the specifications for tall buildings.
The size of the corner region as defined by NBCC (1990) specifications for both low and tall buildings is shown in Figure 3.5.
For the 30m high building, all the taps used in the study are situated in the corner region as defined by NBCC (1990) specifications for tall buildings and the results will be presented in the next section.
In the case of the 10m high building, the taps located between column 13 and 28 (as shown in Figure 3.5) are situated in the edge region provided in the NBCC (1990) specifications for low buildings. The results obtained for these taps are presented in this section.

Figure 4.8 presents mean and peak values of local pressure coefficients measured at two different edge taps (1-20 and 3-22) and their variation with azimuth for all parapets tested. These two taps have been chosen for having the general characteristic trends for local loads in the edge region.

The edge area investigated is very small and close to the roof corner region. Thus, the results of the measurements could not be extended to the entire edge region and the predicted trends are limited to the area studied. It appears that all parapets higher than 0.5m will produce a small increase of local suctions.

Since the edge area studied is very small, only one tributary area is to be considered on the roof edge (as shown in Figure 3.5), concerning the measurement of area-averaged loads. Figure 4.9 shows the effect of azimuth on area-averaged mean and peak pressure coefficients.

The first diagram shows the mean pressure coefficients for eight wind directions and each parapet tested.

The worst pressure coefficients , (which is the maximum value from all wind directions tested), show that the addition of parapets increase the roof suction. As expected, for wind direction between $0^{\circ}$ and $15^{\circ}$ , buildings without a parapet experience the highest suctions; for wind direction between $15^{\circ}$ and $45^{\circ}$ , buildings having parapets lower or equal to 1.5m have higher suctions than those without parapet.

## H = 10 m

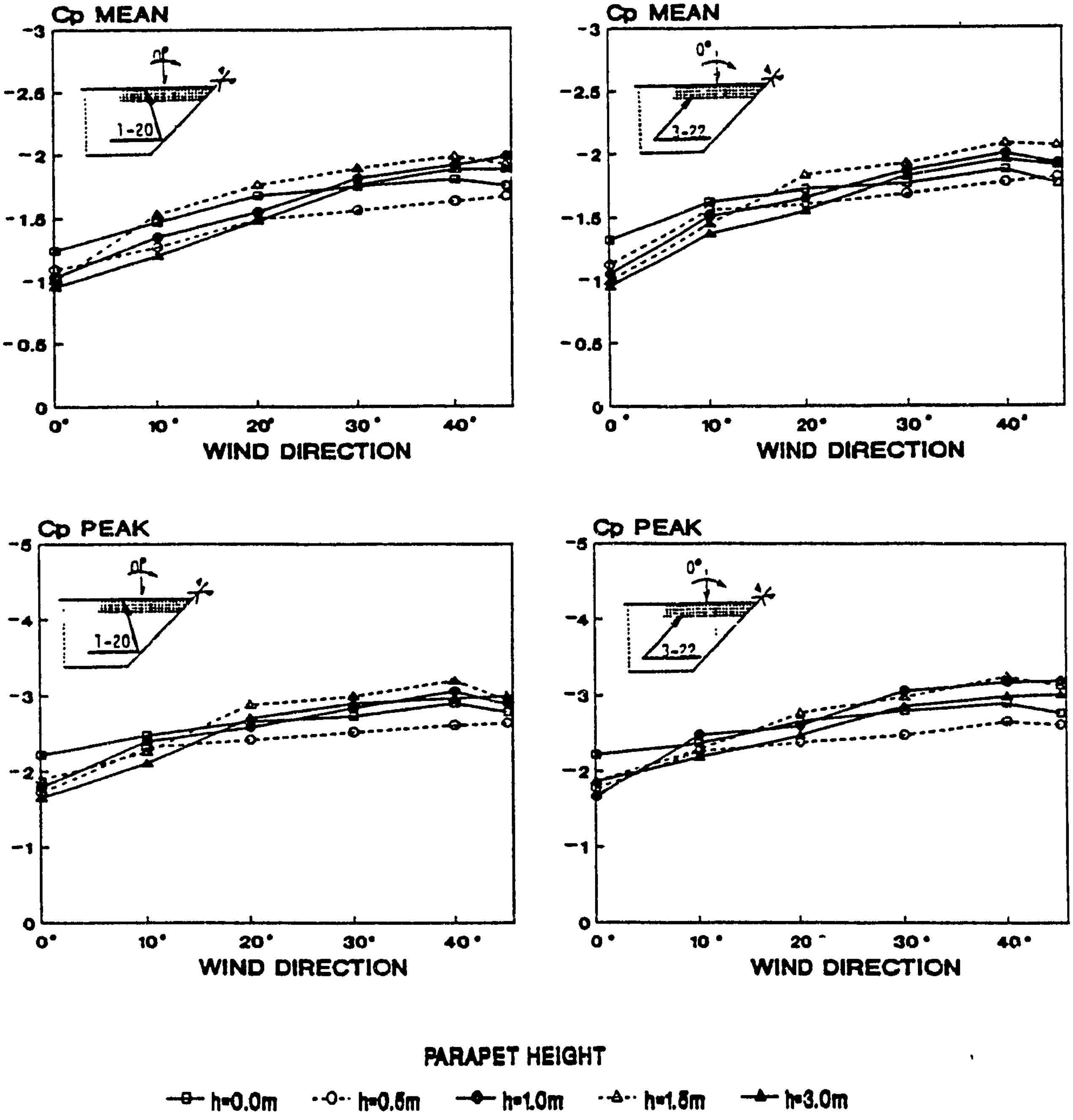


Fig. 4.8 THE EFFECT OF AZIMUTH ON MEAN AND PEAK LOCAL PRESSURE COEFFICIENTS ON ROOF EDGE FOR H=10m (Taps 1-20 & 3-22)

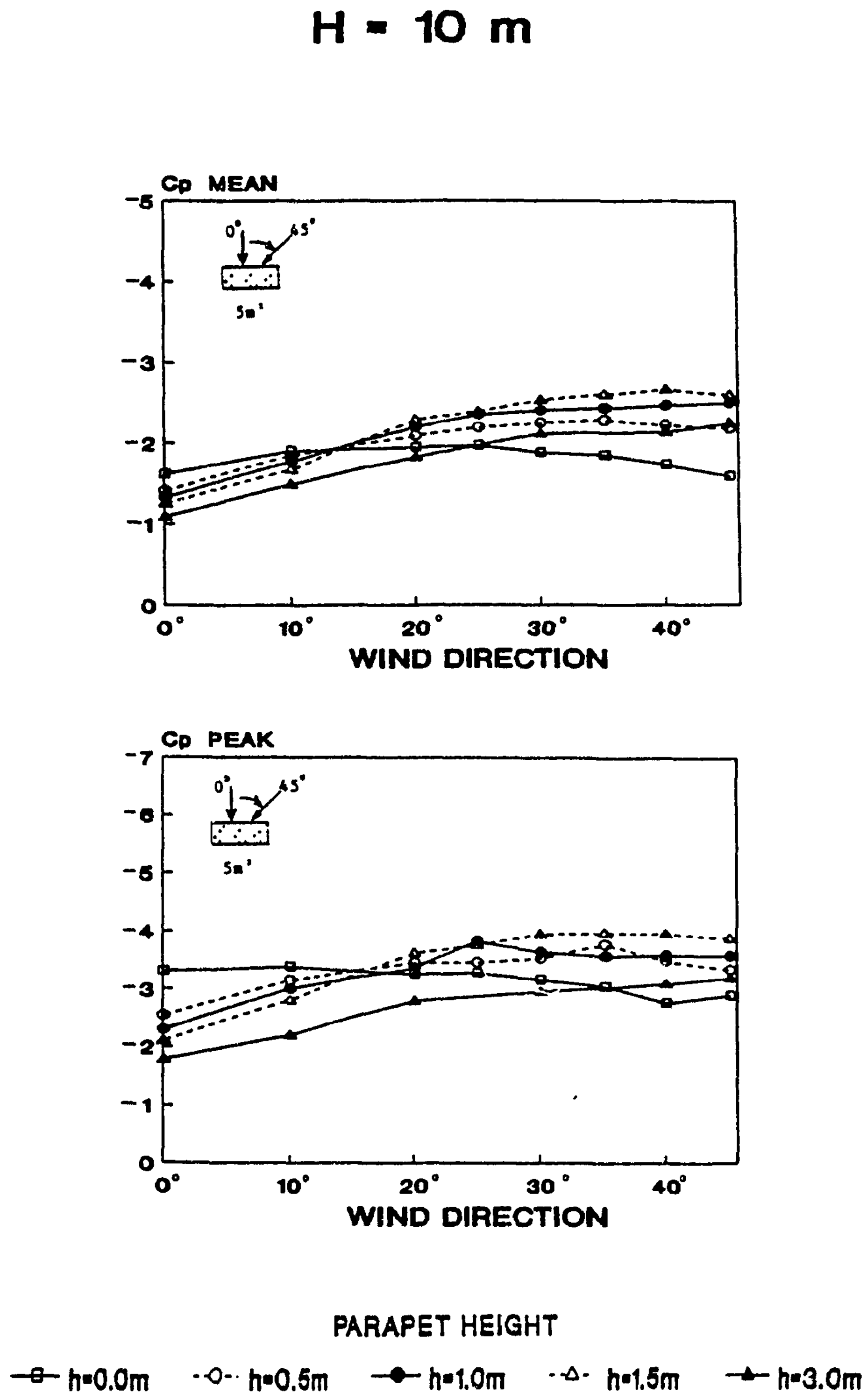


Fig. 4.9 THE EFFECT OF AZIMUTH ON AREA-AVERAGED MEAN AND PEAK EDGE ROOF PRESSURE COEFFICIENTS FOR H=10m

The second diagram shows the peak pressure coefficients for the same tributary areas. Concerning the wind directions between 15° and 45° , parapets lower than or equal to 1.5m increase the uplift pressure coefficients measured, while the peak pressure coefficients are reduced when the wind attack angle is between 0° and 35°, in the presence of a 3m parapet. The results indicate that the pressure coefficients get their highest values mostly for the 45° wind direction, regardless of parapet height. The trend is also apparent in the results obtained for corner regions. However, the increase of roof suctions caused by the parapets is smaller in the case of edge region. This was expected considering the conical vortex flow developed over the roof edges starting with a maximum near the corner. The diameter of the vortex increases and its strength decreases proportionally with distance from the corner. Small eddies may be produced in the vortex cones when parapets are placed across the approaching stream lines and this may cause "a pocket of high turbulence" at the roof corners. Consequently, the suctions are increased significantly.

## 4.5 WIND LOADS ON ROOF CORNERS WITH PARAPETS

This section discusses the changes of roof corner wind loads. Regardless of the existence of parapets, the highest economical losses due to wind action occur on building roof corners for oblique wind directions, for which the magnitude of suction load is maximum.

Some previous studies (Columbus, 1972, Kind, 1974, Kramer, 1985) have found that roof corner loads are reduced significantly due to parapets. However, some other works (Davenport, 1974, Lythe and Surry, 1983, Stathopoulos, 1982, Stathopoulos and Baskaran, 1986) have found that parapets may have a different effect on roof corner suctions.

Stathopoulos (1982), after a comprehensive experimental study on the effect of parapets on low buildings, has found that the roof corners experience a high suction in the presence of parapets; the study by Lythe and Surry (1983) has confirmed this finding,too. More recently, experimenting with the effect of parapets on low and high buildings, Stathopoulos and Baskaran (1986) have observed that all parapets seem to increase the corner suctions in the case of lower buildings whereas only low parapets (less than 1m high) have the same effect on tall buildings. It is, therefore, of interest to examine the effect of parapets on low and intermediate roof corners in detail.

In order to obtain a full assessment of the effect of parapets, very low and high parapets from 0 to 3m have been tested.

The effect of azimuth on mean and peak local pressure coefficients on roof corner points for all parapets tested concerning low buildings are presented in Figures 4.10 and 4.11. Based on these data, the following remarks can be made:

1.- the maximum suctions are obtained for a parapet approximately 1m high for all corner taps;

2.- 0.5m and 1m parapet heights increase the suctions for the first row's tap for wind directions between 30° and 45°, while all parapet heights tested have the same effect for the fourth row's tap for wind directions between 20° and 45°.

Generally, for wind directions between 0° and 20° , buildings without parapets show higher suctions than buildings with parapets. This trend is clearer for the mean values than for the peaks. Regarding the magnitude of the suctions due to the parapet, their increase is the lowest for the first row's tap and highest for the fourth row's.

Figures 4.12 and 4.13 show the effect of azimuth on mean and peak local pressure coefficients on roof corner points for the 30m high building.

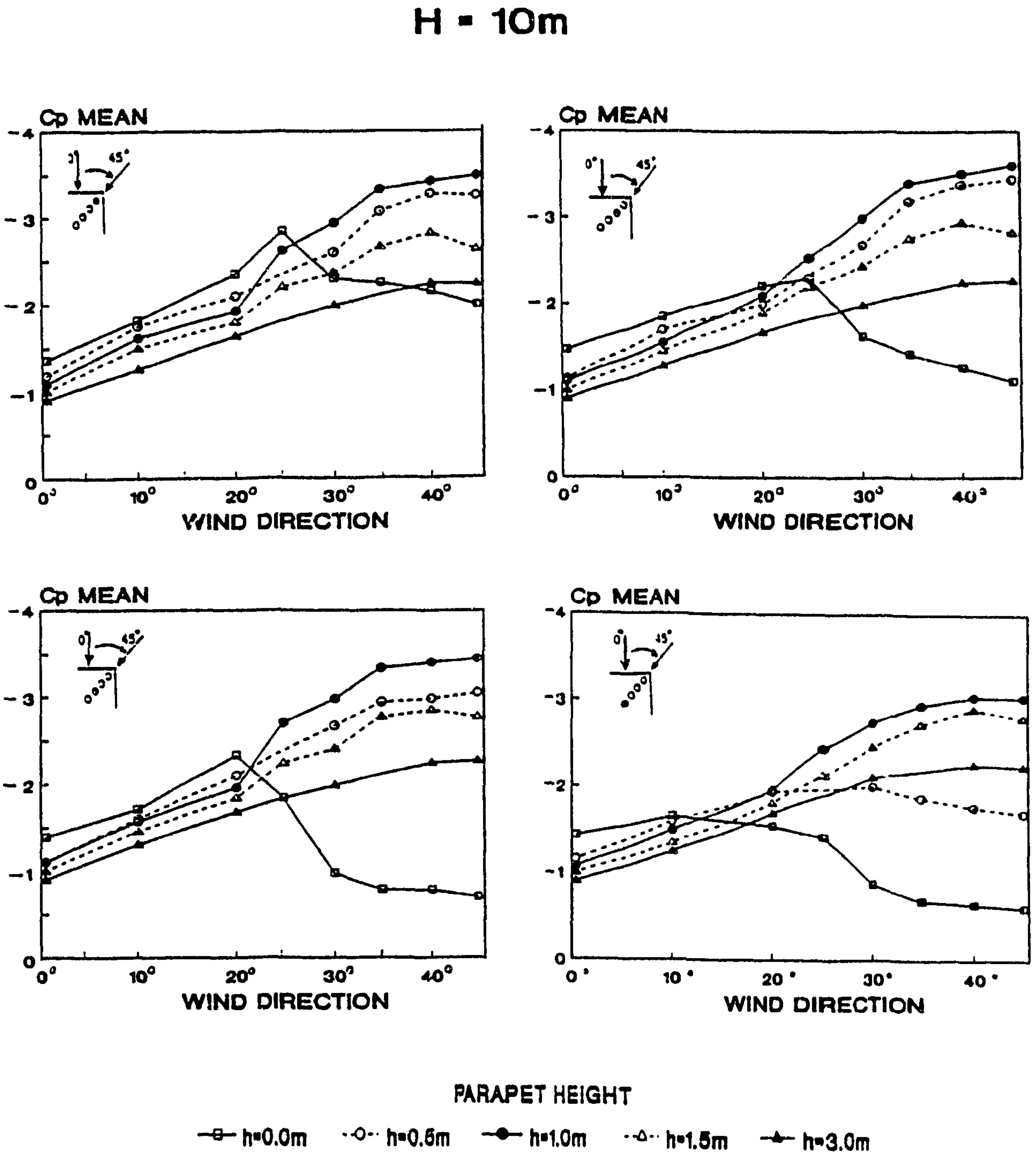


Fig. 4.10 THE EFFECT OF AZIMUTH ON MEAN LOCAL PRESSURE COEFFICIENTS ON ROOF CORNER POINTS FOR H=10m

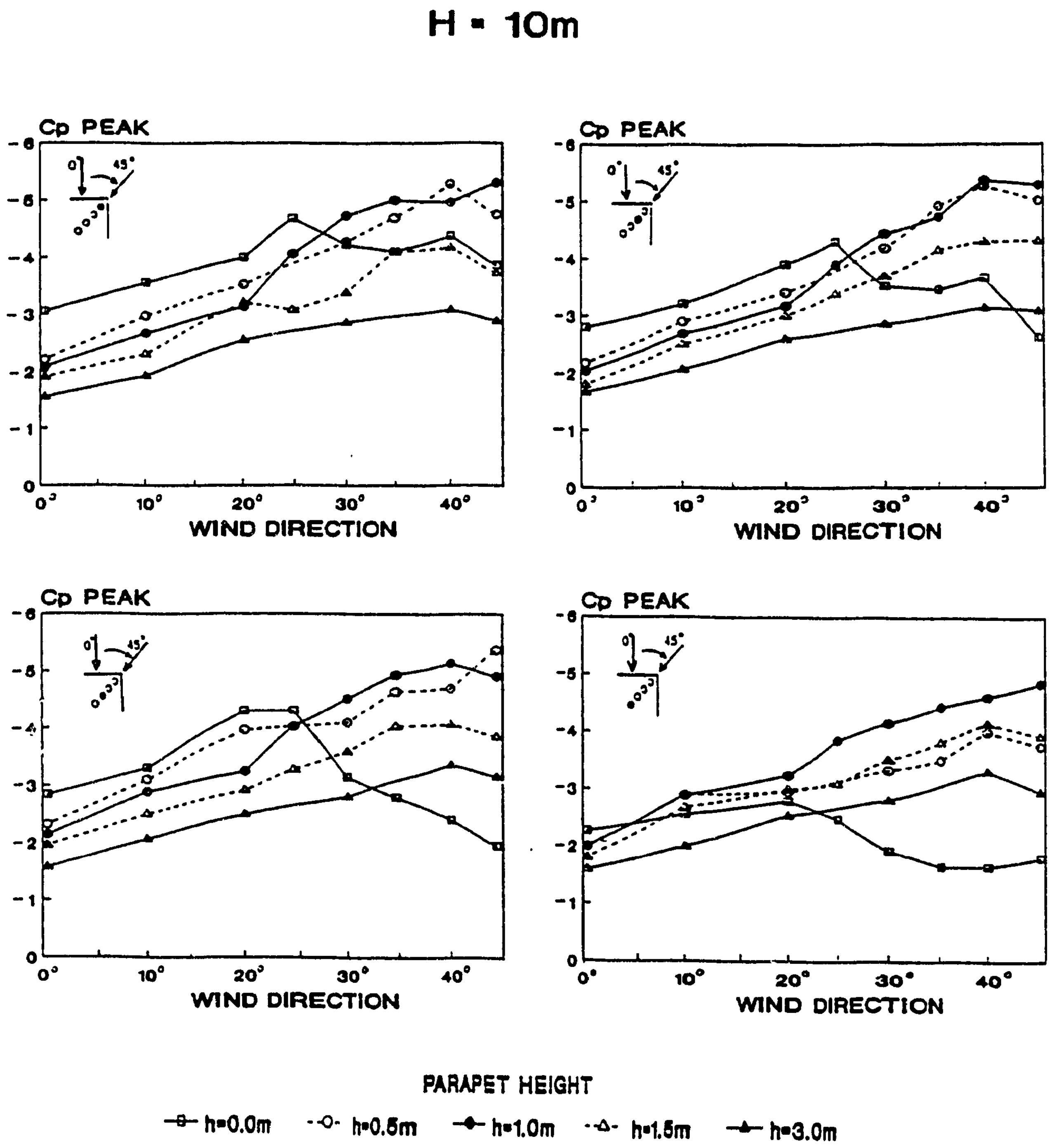


Fig. 4.11 THE EFFECT OF AZIMUTH ON PEAK LOCAL PRESSURE COEFFICIENTS ON ROOF CORNER POINTS FOR H=10m

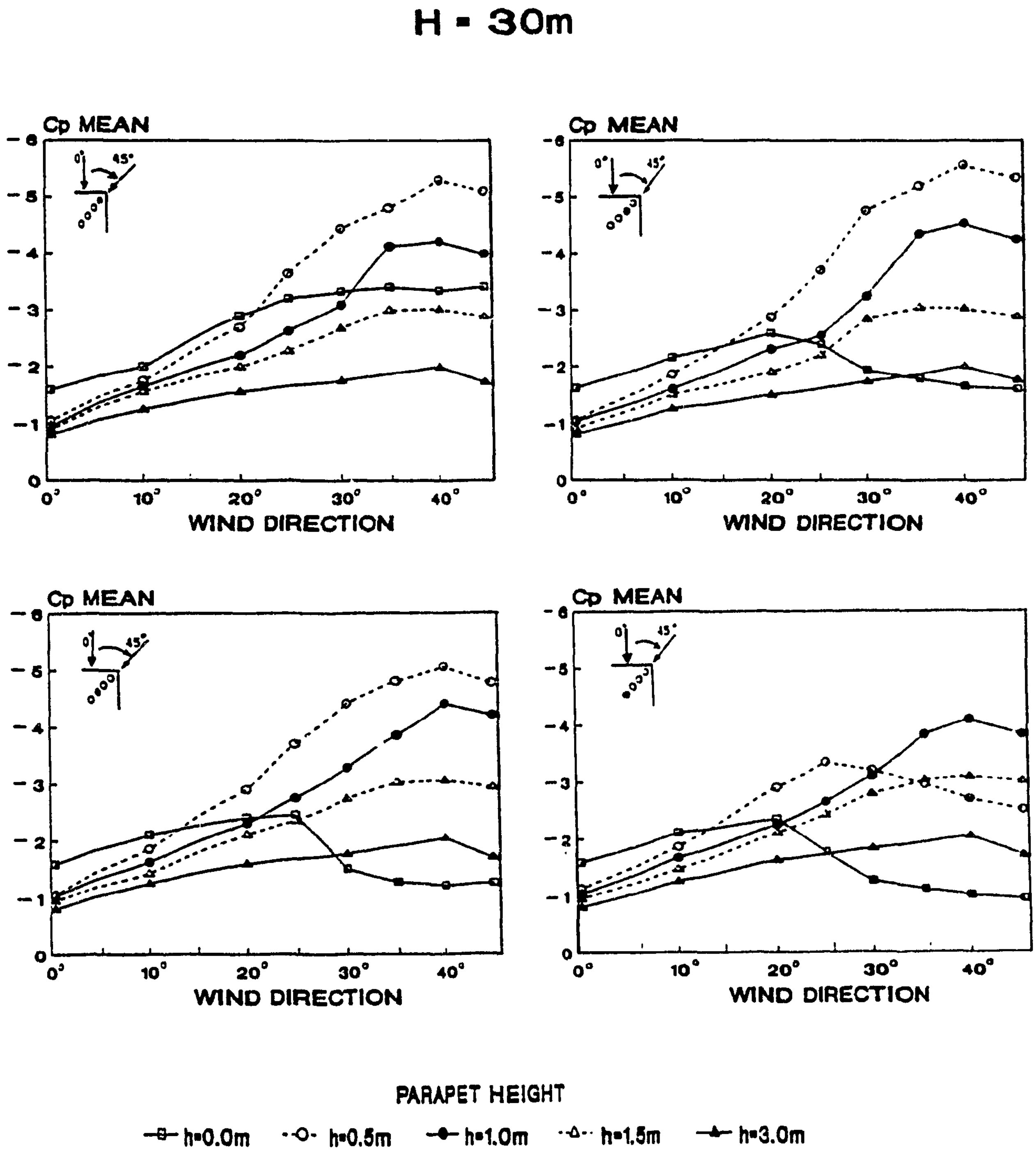


Fig. 4.12 THE EFFECT OF AZIMUTH ON MEAN LOCAL PRESSURE COEFFICIENTS ON ROOF CORNER POINTS FOR H=30m

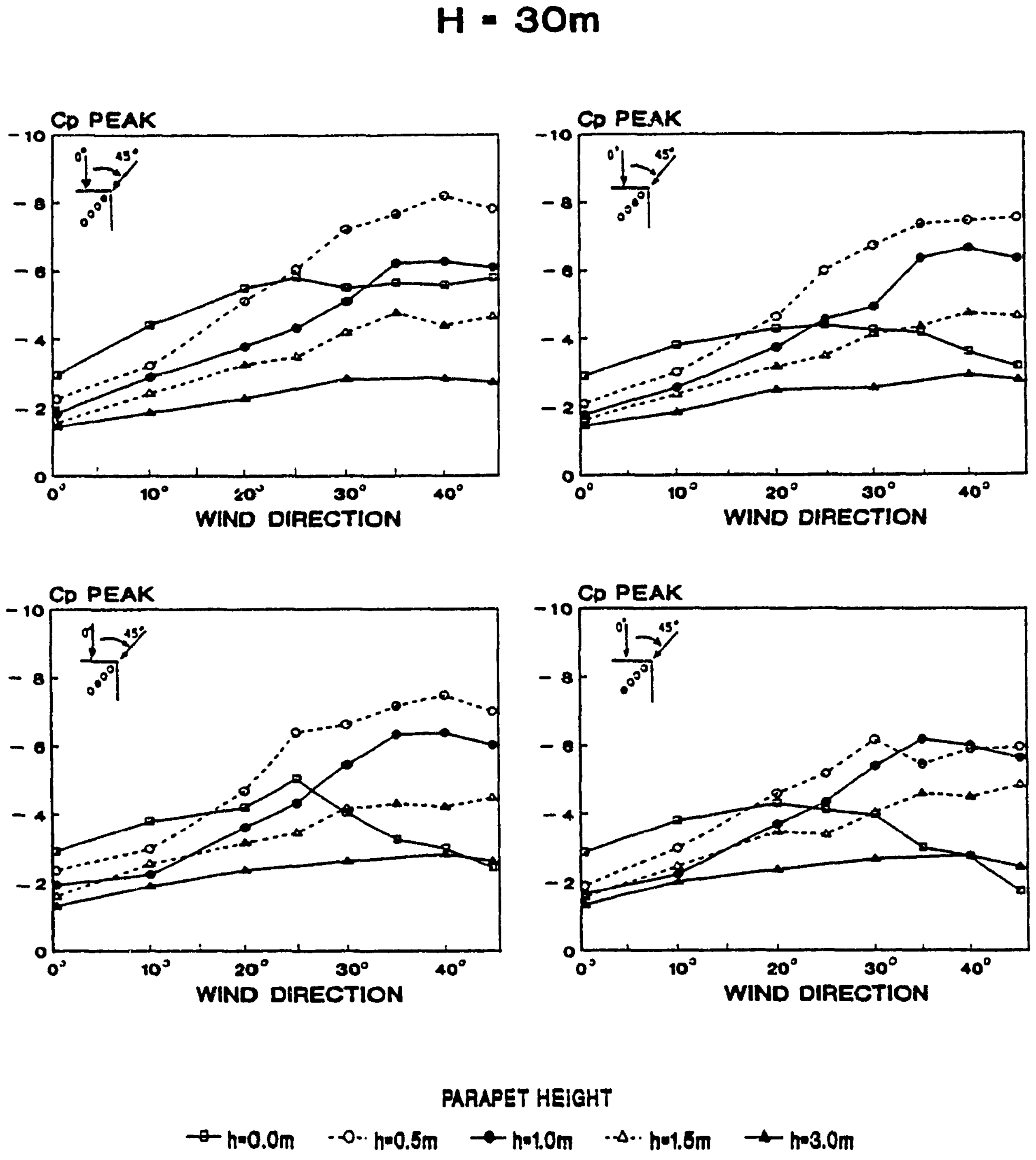


Fig. 4.13 THE EFFECT OF AZIMUTH ON PEAK LOCAL PRESSURE COEFFICIENTS ON ROOF CORNER POINTS FOR H=30m

For these buildings, the highest increase of roof suctions is generally obtained when a 0.5m parapet is attached.

A 0.5m to 1m parapet attached to the roof will increase the suction measured at the first row tap for cornering wind directions (between 25° and 45°). All parapets lower than 3.0m have the same effect for the fourth row's tap, for wind directions between 25° and 45°.

Concerning the magnitude of the suctions due to the parapet, their increase is the lowest for the first row's tap and gets its highest value for the third row tap.

These diagrams for H=10m and H=30m show that the proximity of the corner tap to the roof edge is a very important factor for the magnitude of high local suctions, and for the analysis of parapet's influence on roof corner suctions.

Previous studies have used models with just one tap on the corner with different distances to the roof edge, and they may have missed the highest suctions and the effect of parapet on their magnitude. For example, for buildings without parapet, for azimuths between 30° to 45° , pressure coefficients measured at the first row have been found to be 2 to 3 times higher than those measured at the fourth row, corresponding to the "usual" corner points.

Fortunately, these high suctions affect only a very small portion of the roof corner because of the high gradient

of their reduction with distance from the edge.
The variation of pressure coefficients with parapet height, on roof corner points, for both buildings examined is presented in Figure 4.14. A comparison of the two diagrams shows that the effect of parapets on roof corner suctions is influenced by the building height. All parapets seem to increase the suctions in the case of low buildings, whereas only low parapets (less than 1.5m) have the same effect on intermediate buildings. These diagrams show, too, the importance of corner tap location on the pressure coefficients measured for buildings without parapet and with low parapets (1m and less). This was expected because once parapet height increases, the suctions become lower, moving inwards the roof.

The variation of the worst local pressure coefficients with parapet height for both buildings examined is presented in Figure 4.15. Data indicate that parapets of 0.5m and 1m increase the corner suctions in the case of low buildings, whereas only parapets of 0.5m have the same effect on intermediate buildings. It is also interesting to notice that pressure coefficients get their highest value mostly for 1m parapets in the case of low buildings, whereas the highest value for intermediate buildings is measured for 0.5m parapet.
The effect of azimuth on local pressure coefficients measured at two taps situated at about 6.8m from the corner (1-20 and 3-22 as shown in Figure 3.5) is shown in

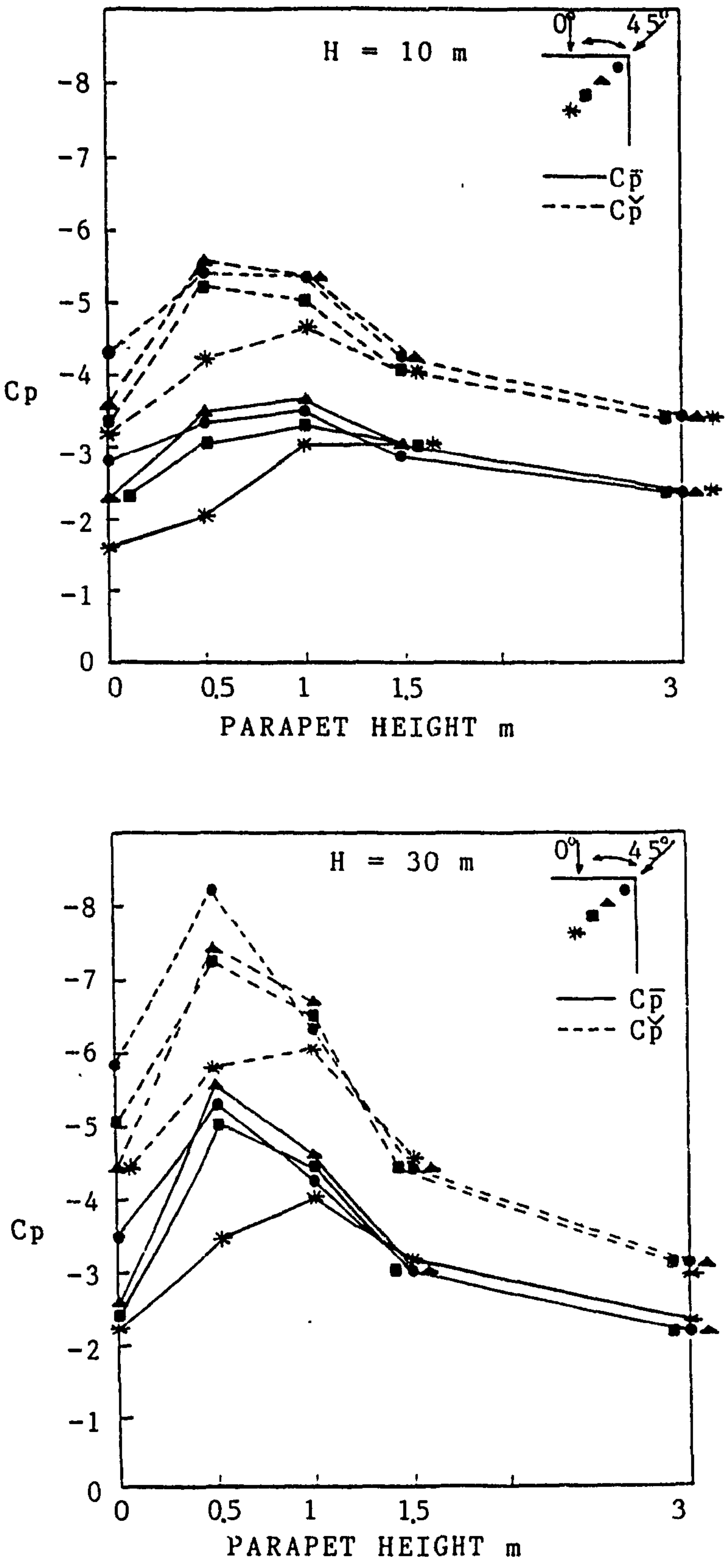


**Fig. 4.14 THE EFFECT OF PARAPETS ON MOST CRITICAL MEAN AND PEAK LOCAL PRESSURE COEFFICIENTS ACTING ON ROOF CORNER POINTS**

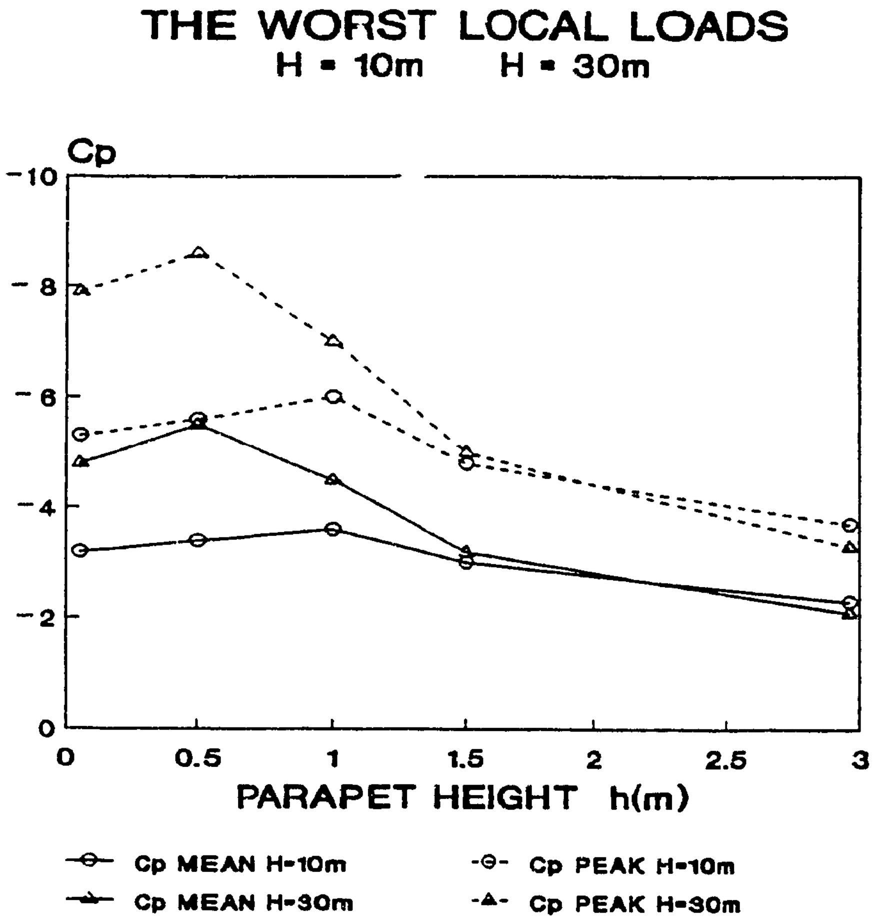


Fig. 4.15 THE EFFECT OF PARAPETS ON THE MOST CRITICAL MEAN AND PEAK LOCAL PRESSURE COEFFICIENTS

Figure 4.16, for the 30m high building. These two taps are located in the corner region in accordance with the N.B.C.C. (1990) specifications. The effect of parapets on pressure coefficients measured is quite different from the trend found for taps very close to the roof corner, namely that any parapet increases the local suctions.
So, it becomes clear that in this region, the increase of pressure coefficients due to any parapets ceases to exist.

It is of interest to consider area-averaged pressures acting of roof corners. Mean and peak pressure coefficients measured for tributary areas of equal magnitude within the roof corner but at different distances from the edges are presented in Figures 4.17, 4.18, 4.19 and 4.20.
The size of the areas and the locations can be seen in Figure 3.5. Generally speaking, the trend is the same with that of local loads for both buildings tested.
Figure 4.21 shows other corner area-averaged pressure coefficients, measured on areas of larger size for both buildings. These areas are located inside the corner region according to N.B.C.C. (1990) provisions for both building heights (see Figure 3.5). The results show similarity to the data obtained for local loads and to previously measured area-averaged corner pressures, namely, parapets lower or equal to 1.5m increase the pressure coefficients for cornering wind directions.

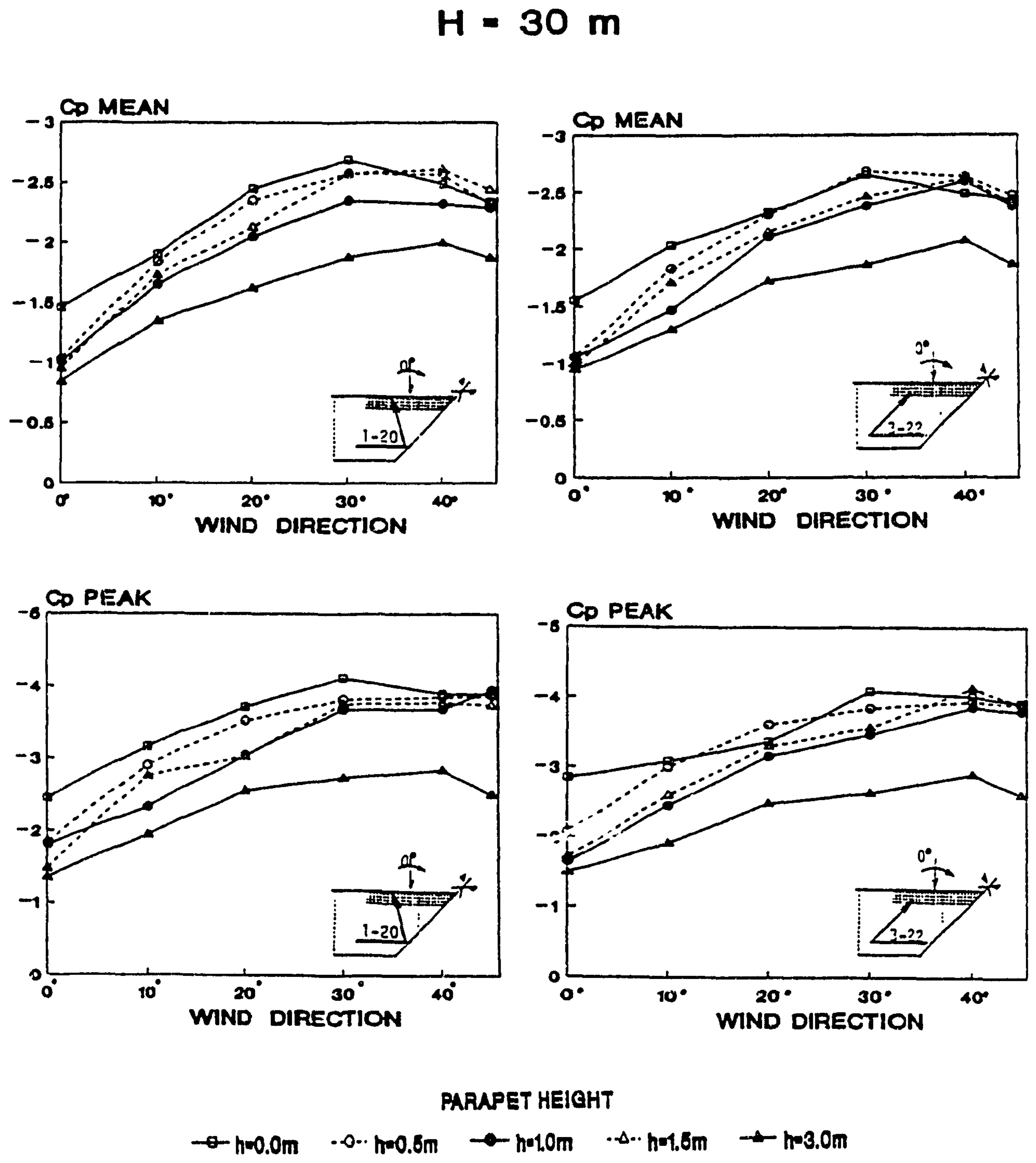


Fig. 4.16 THE EFFECT OF AZIMUTH ON MEAN AND PEAK LOCAL PRESSURE COEFFICIENTS FOR H=30m (Taps 1-20 & 3-22)

H = 10 m

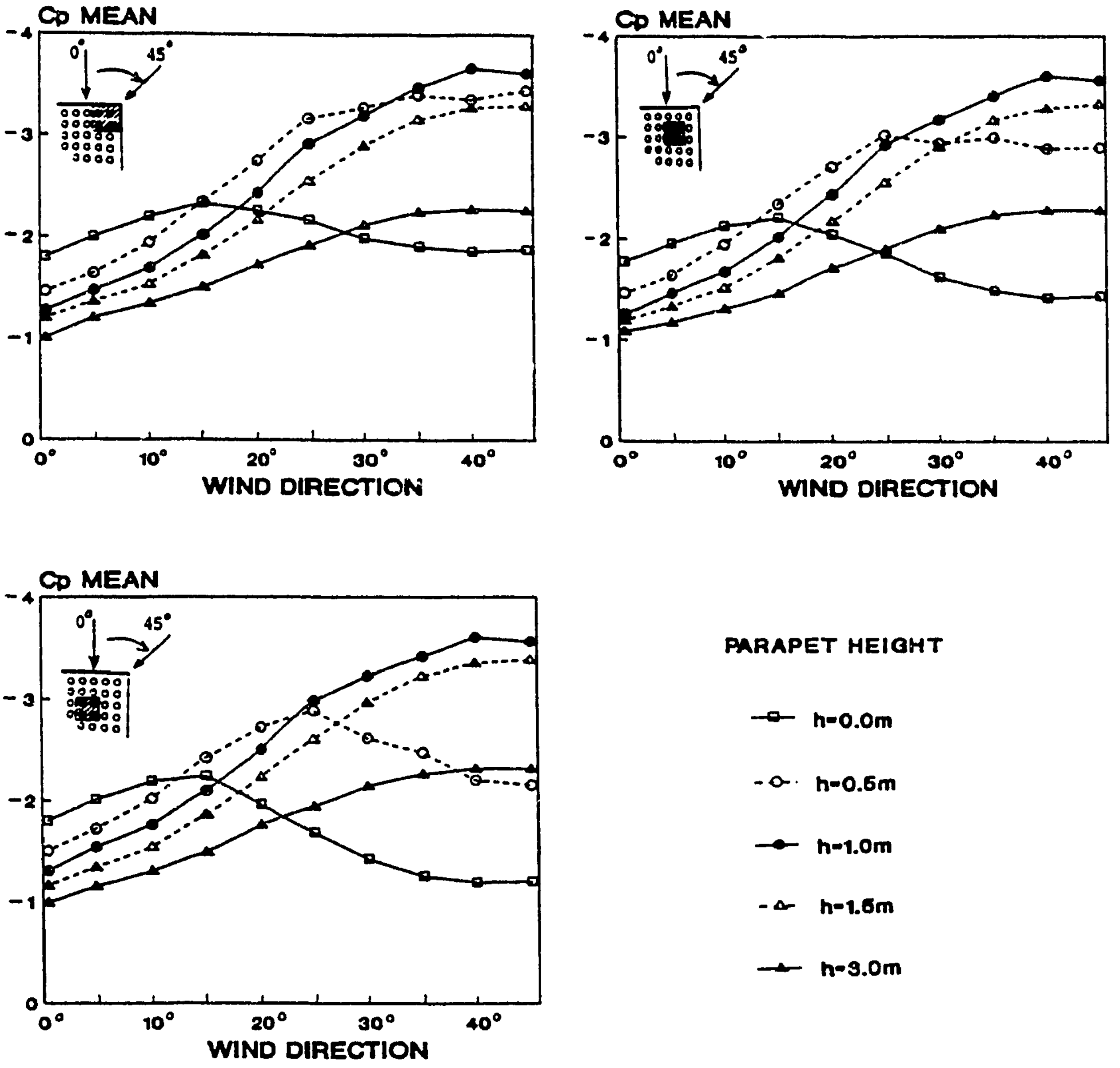


Fig. 4.17 THE EFFECT OF AZIMUTH ON AREA-AVERAGED MEAN PRESSURE COEFFICIENTS ACTING ON ROOF CORNERS FOR H=10m

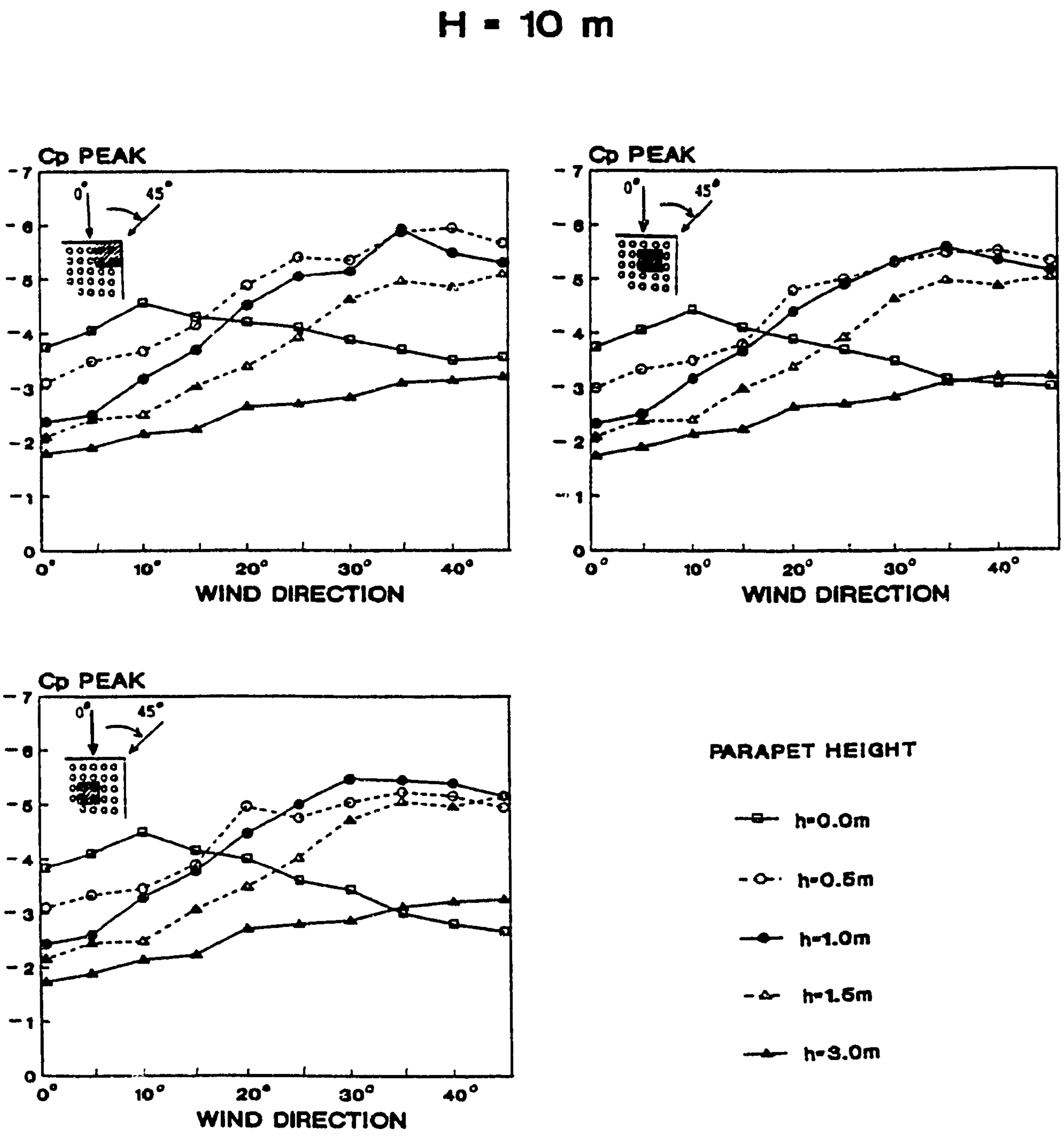


Fig. 4.18 THE EFFECT OF AZIMUTH ON AREA-AVERAGED PEAK PRESSURE COEFFICIENTS ACTING ON ROOF CORNERS FOR H=10m

H = 30 m

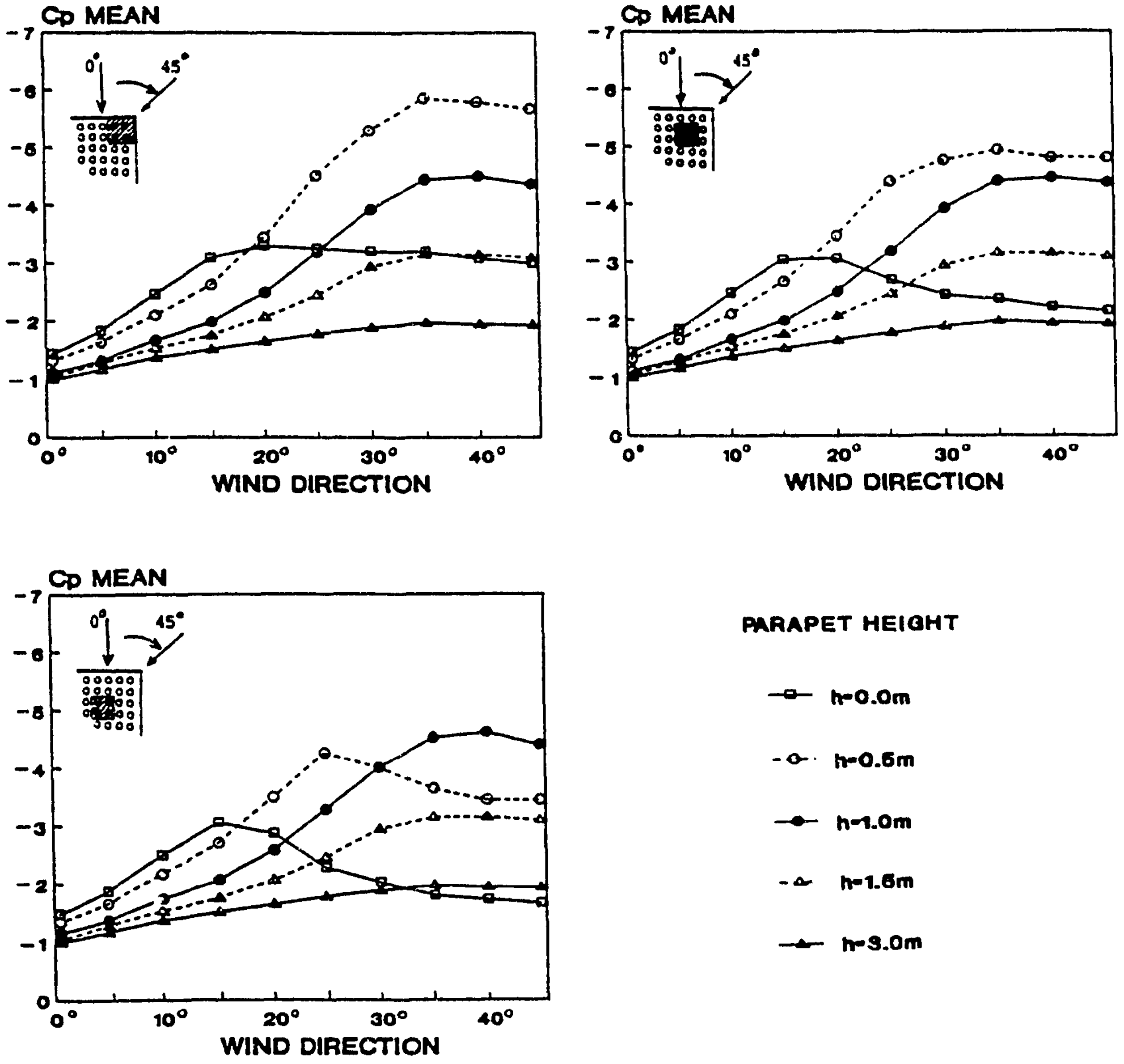


Fig. 4.19 THE EFFECT OF AZIMUTH ON AREA-AVERAGED MEAN PRESSURE COEFFICIENTS ACTING ON ROOF CORNERS FOR H=30m

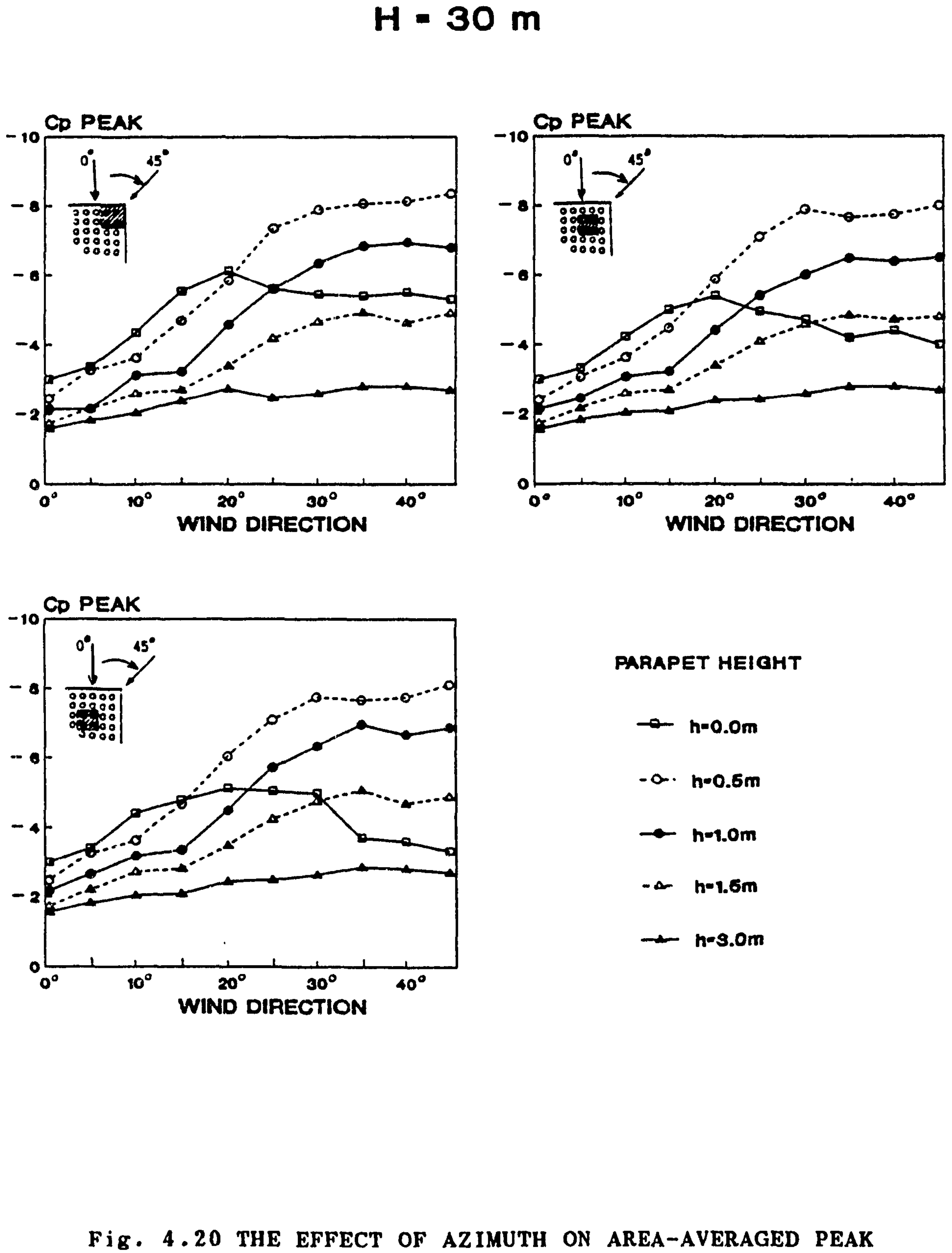


Fig. 4.20 THE EFFECT OF AZIMUTH ON AREA-AVERAGED PEAK PRESSURE COEFFICIENTS ACTING ON ROOF CORNERS FOR H=30m

Regarding a 3m parapet, in the case of H=30m, it decreases the suctions for any wind directions, but for H=10m, the suctions decrease in the case of frontal wind direction and show a small increase for the cornering wind direction.

Figure 4.22 presents the effect of azimuth on area-averaged mean and peak pressure coefficients measured along one side of the corner (see Figure 3.5) for a building with height H=30m.

The trend concerning this area is similar to that found for the corresponding local loads (as shown in Figure 4.16). No parapet increases the pressure coefficients. Moreover, the higher the parapet is, the larger is the pressure coefficients' reduction.

In conclusion, for H=30m, regarding the changes in wind loading caused by parapets, two zones can be defined:

- the first zone, between points 1 and 13 (4m) in which parapets lower than 1.5m increase the roof suctions;
- the second zone, between points 14 and 28 (4m) in which no parapets increase the roof suctions.

In summary, it is clear that low parapets (h < = 1m) in any building increase significantly the roof corner pressure coefficients for oblique wind directions. This trend is valid for the corner region of low buildings H=10m and for the first zone of the corner region for intermediate buildings H=30m, as previously defined.

It is well known that for simple flat roofs under oblique wind directions, strong conical vortex sheets induce suctions along the roof edges starting with maximum at the corner. Small eddies may be produced in the vortex cone, when low parapets are placed across the approaching stream lines and this may cause a "pocket of high turbulence" at the roof corners. Consequently, the suctions increase significantly. Wind tunnel studies on flow visualisation may also provide useful information regarding wind interaction with building roofs with various parapets, but this was not attempted in this study.

## 4.6 SUBURBAN EXPOSURE

To examine the effect of parapets on roof wind loading in suburban terrain, both building heights have been tested for several wind directions. Typical results for mean and peak pressure coefficients are presented in contour form in Figures 4.23 - 4.26. Thus, Figures 4.23 and 4.25 show contour graphs for buildings without parapets, whereas Figures 4.24 and 4.26 show graphs for buildings with 0.5m parapets. Comparing the graphs, it appears that a 0.5m parapet increases the corner suctions for both building heights tested.

The effect of azimuth on area-averaged mean pressure coefficients measured for tributary areas of equal magnitude within the roof corner having different

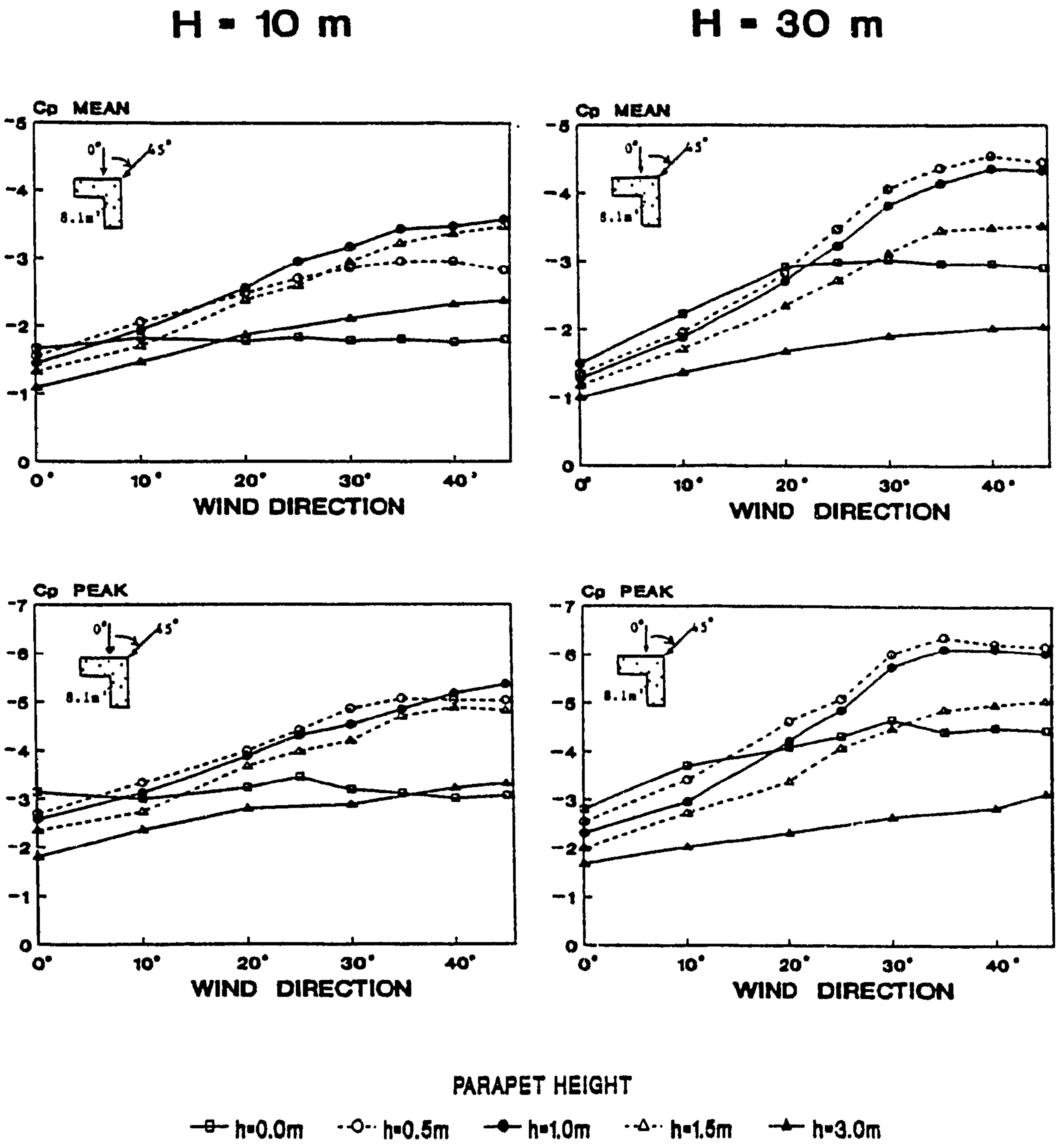


Fig. 4.21 THE EFFECT OF AZIMUTH ON AREA-AVERAGED MEAN AND PEAK PRESSURE COEFFICIENTS FOR H=10m & H=30m

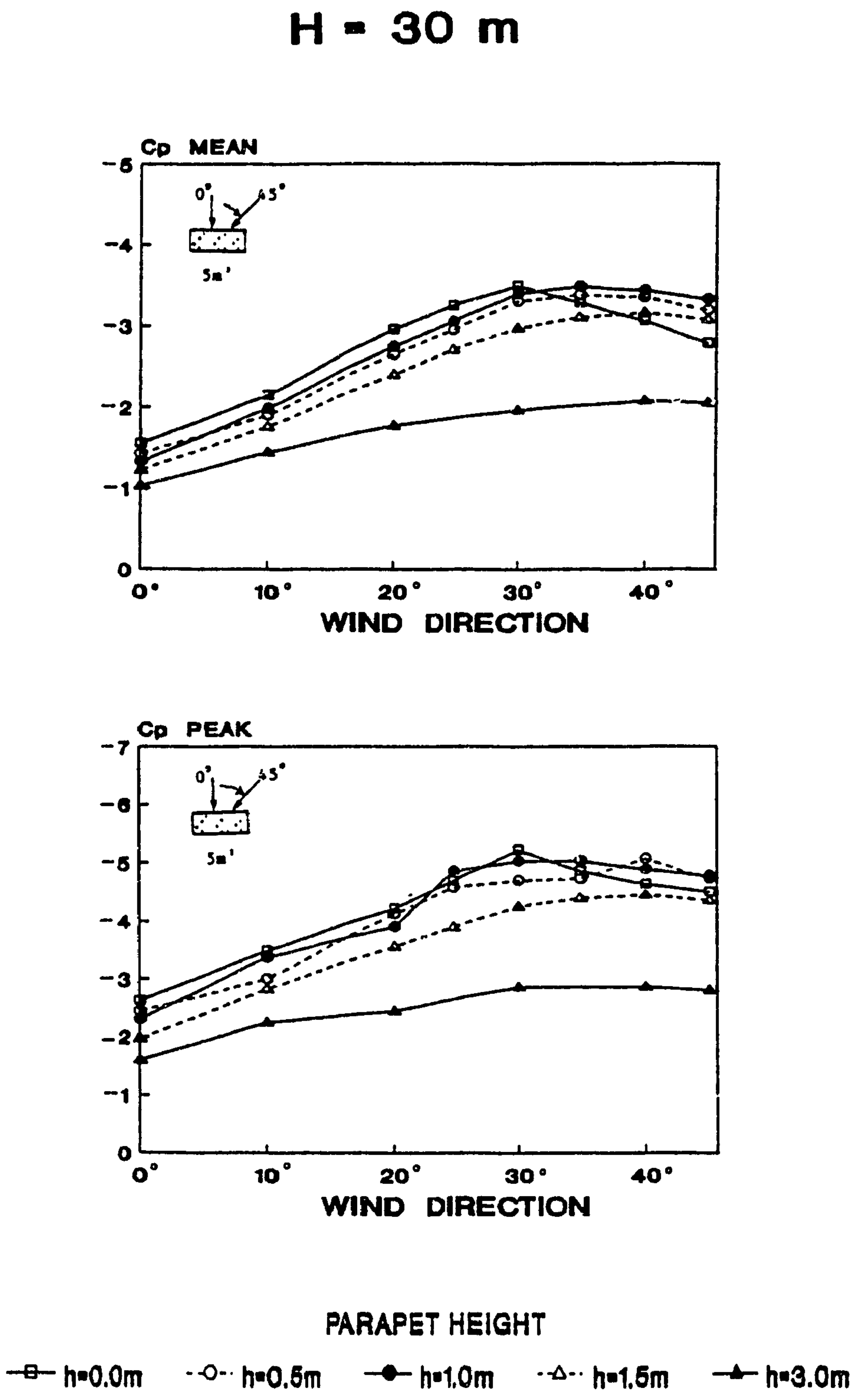


Fig. 4.22 THE EFFECT OF AZIMUTH ON AREA-AVERAGED MEAN AND PEAK PRESSURE COEFFICIENTS FOR H=30m

distances from the edge are presented in Figures 4.27 and 4.28. Concerning the effect of parapet height on roof suctions, the first one shows that a 1m high parapet produces the largest increase of pressure coefficients for H=10m and the second one reveals that in the case of a H=30m, a 0.5m parapet produces the highest increase. Regarding the magnitude of the increase, the largest one is measured for the areas situated at the farthest distance from the edge concerning both building heights. The same trends were found for open country terrain. Comparing these results with those of open country exposure, mean pressure coefficients have comparable magnitude with that found for open country exposure, while peak pressure coefficients are higher in suburban terrain. This is caused by the increased turbulence of the flow, but it should be emphasized that the higher magnitude of peaks does not necessarily imply higher suction loads on the roof corners. This happens because these values are associated with a lower dynamic velocity pressure at roof height (see the "Velocity Profiles" diagram presented in Figure 3.2).

However, the influence of parapets on corner suctions appears similar to that found in the open country terrain.

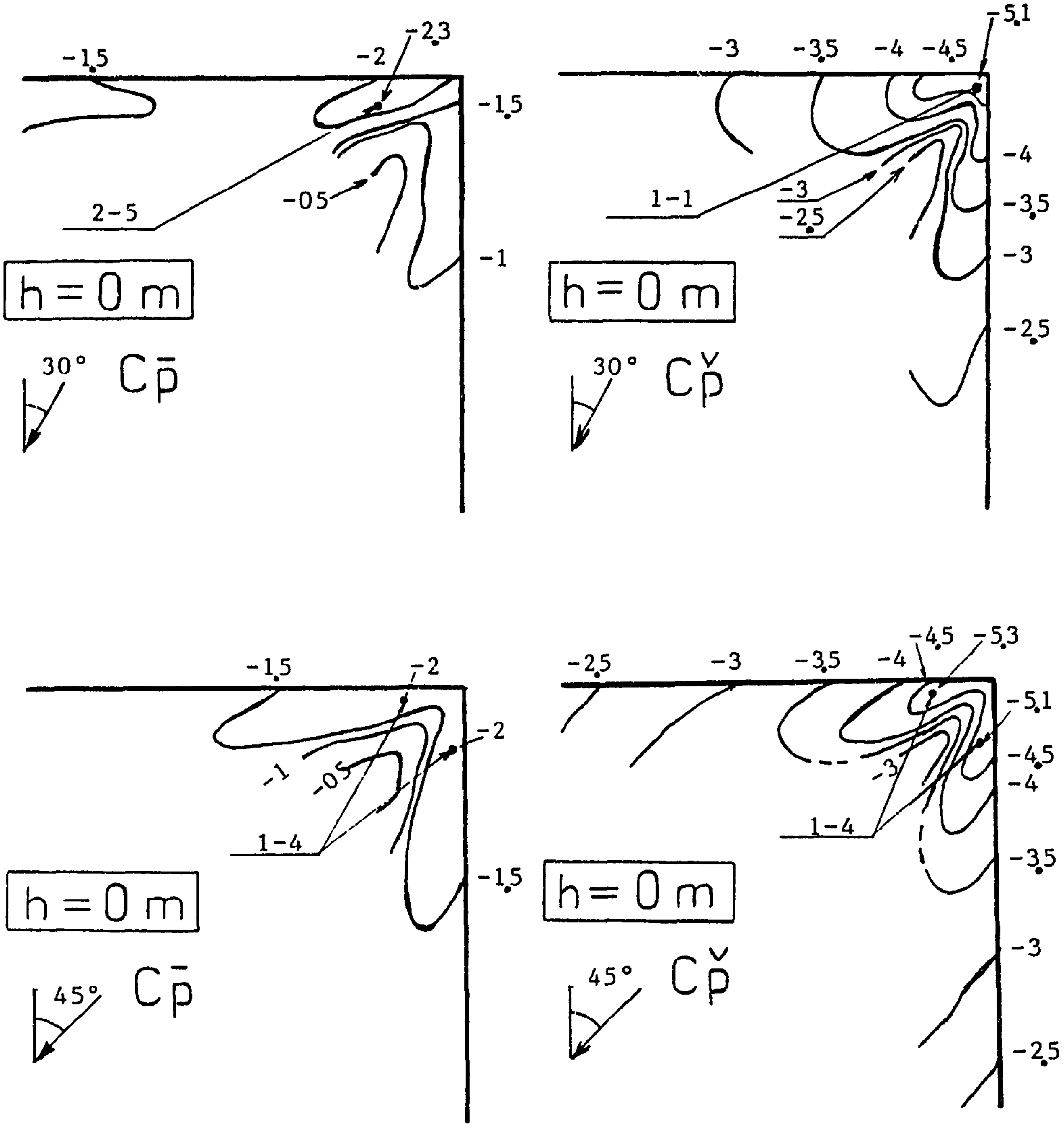


Fig. 4.23 CONTOURS OF MEAN AND PEAK PRESSURE COEFFICIENTS FOR H=10m h=0m SUBURBAN TERRAIN

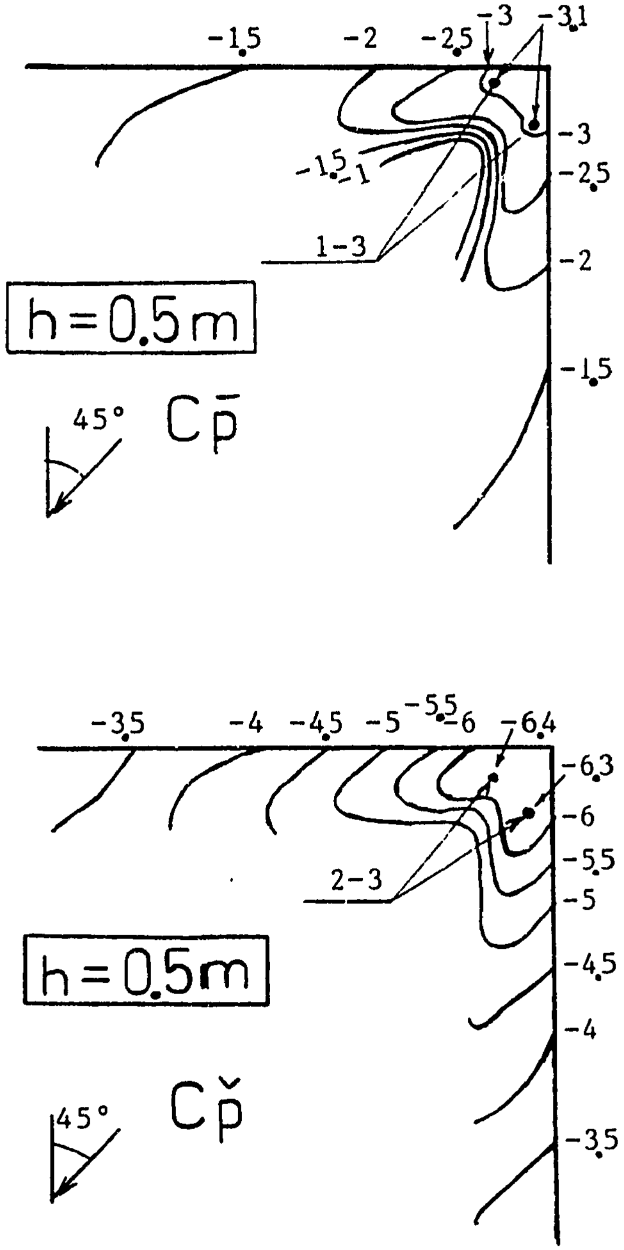


Fig. 4.24 CONTOURS OF MEAN AND PEAK PRESSURE COEFFICIENTS FOR H=10m h=0.5m SUBURBAN TERRAIN

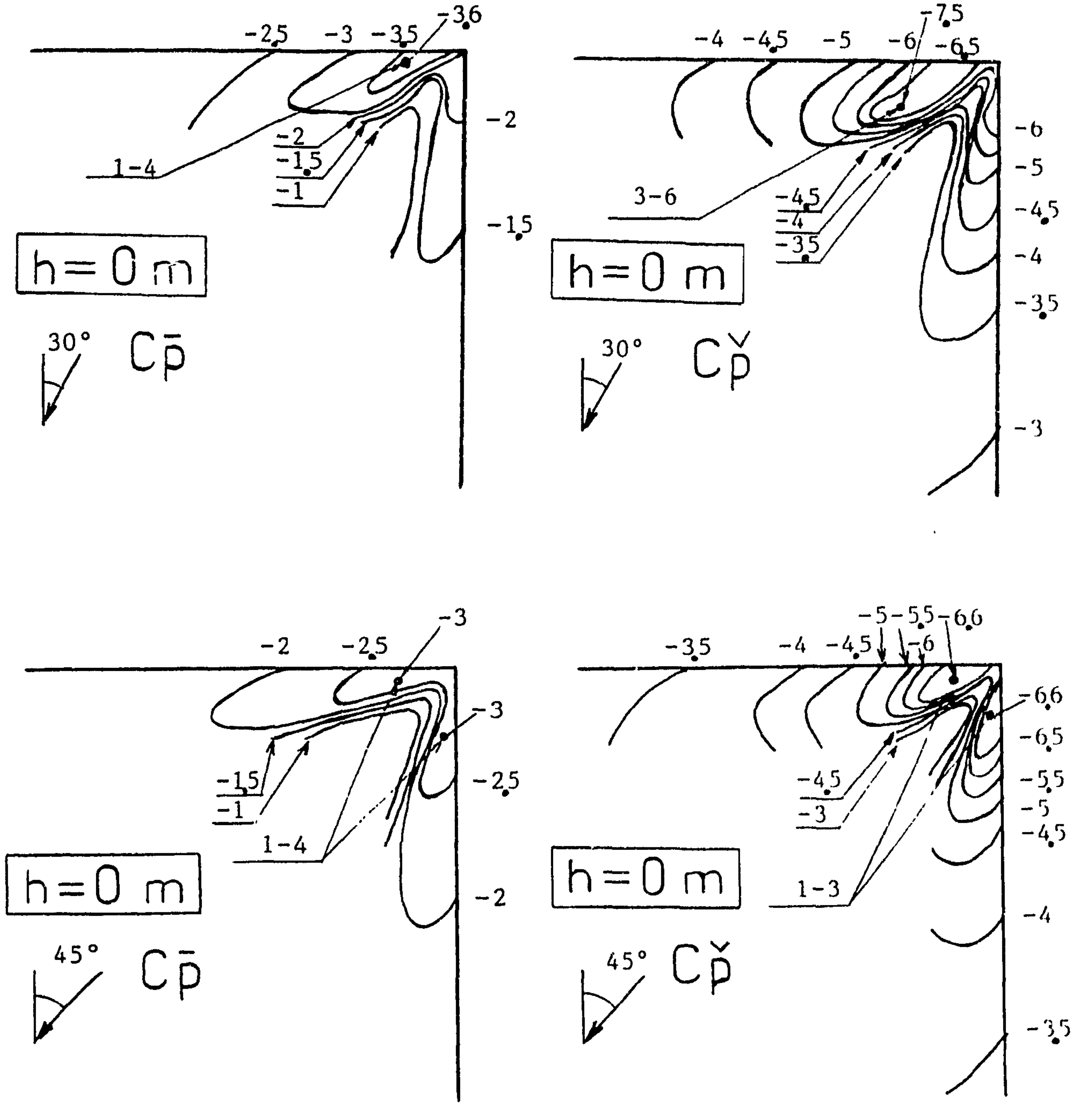


Fig. 4.25 CONTOURS OF MEAN AND PEAK PRESSURE COEFFICIENTS FOR H=30m h=0m SUBURBAN TERRAIN

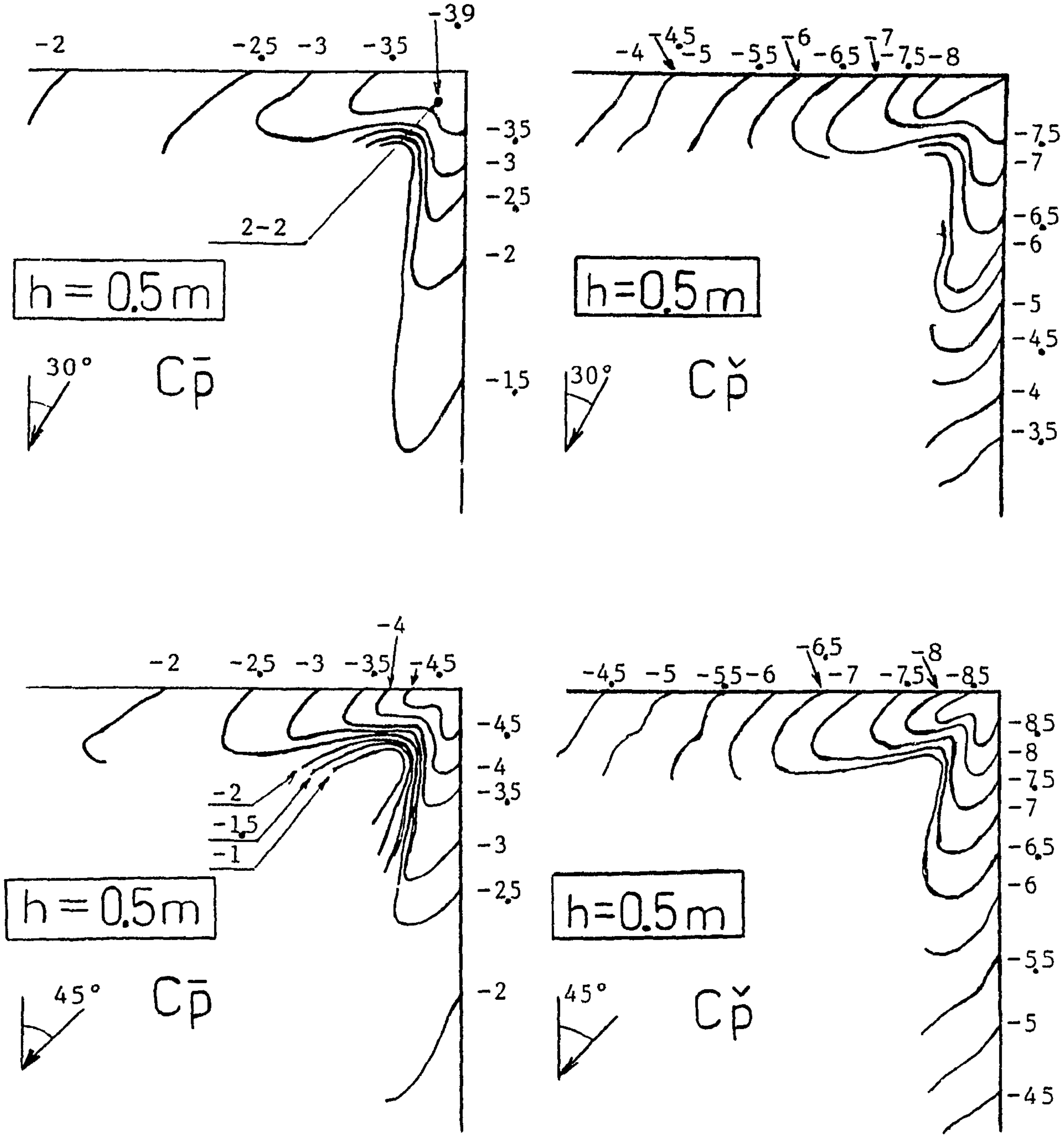


Fig. 4.26 CONTOURS OF MEAN AND PEAK PRESSURE COEFFICIENTS
FOR H=30m h=0.5m SUBURBAN TERRAIN

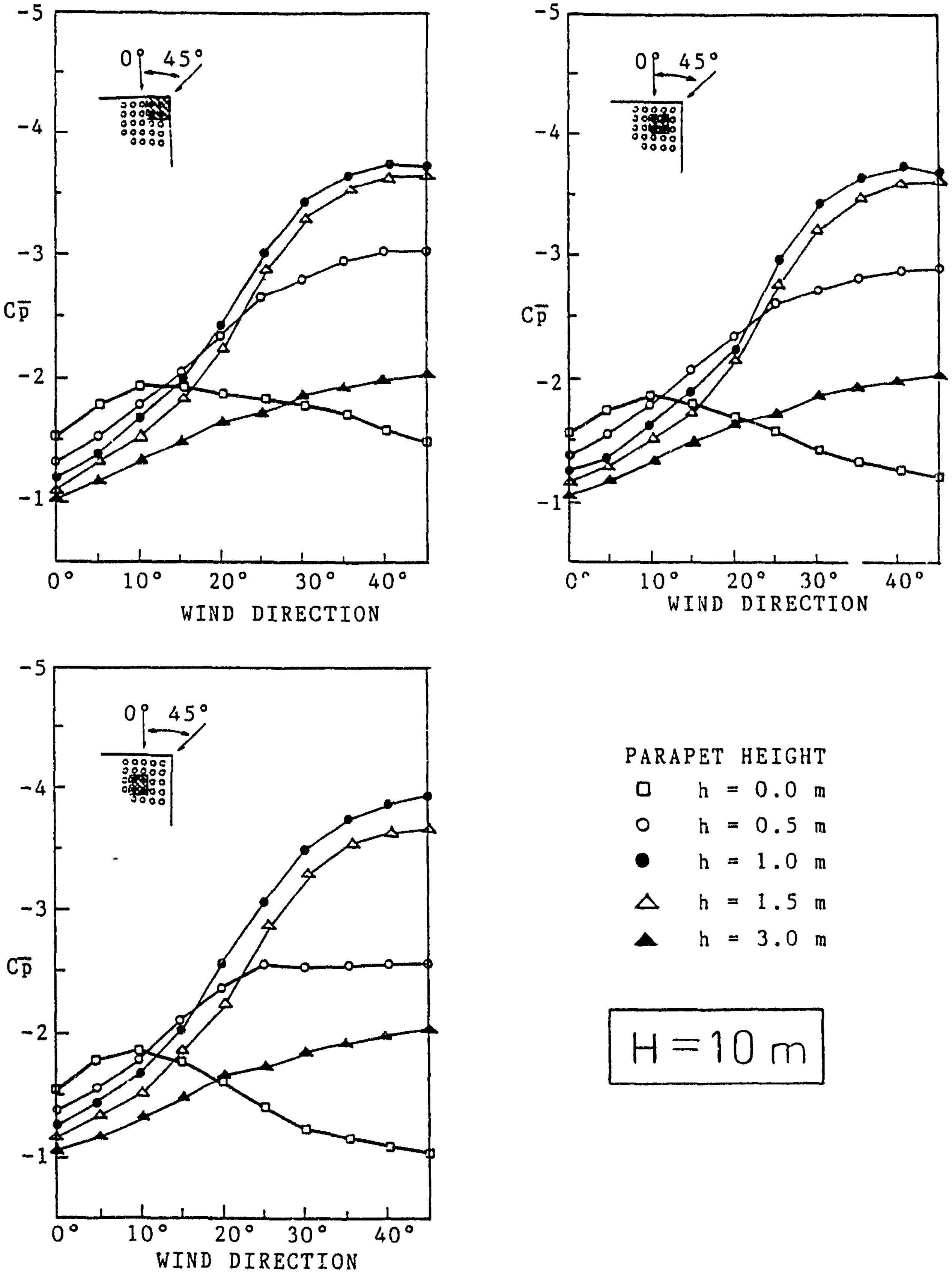


**Fig. 4.27 THE EFFECT OF AZIMUTH ON AREA-AVERAGED MEAN PRESSURE COEFFICIENTS FOR H=10m SUBURBAN TERRAIN**

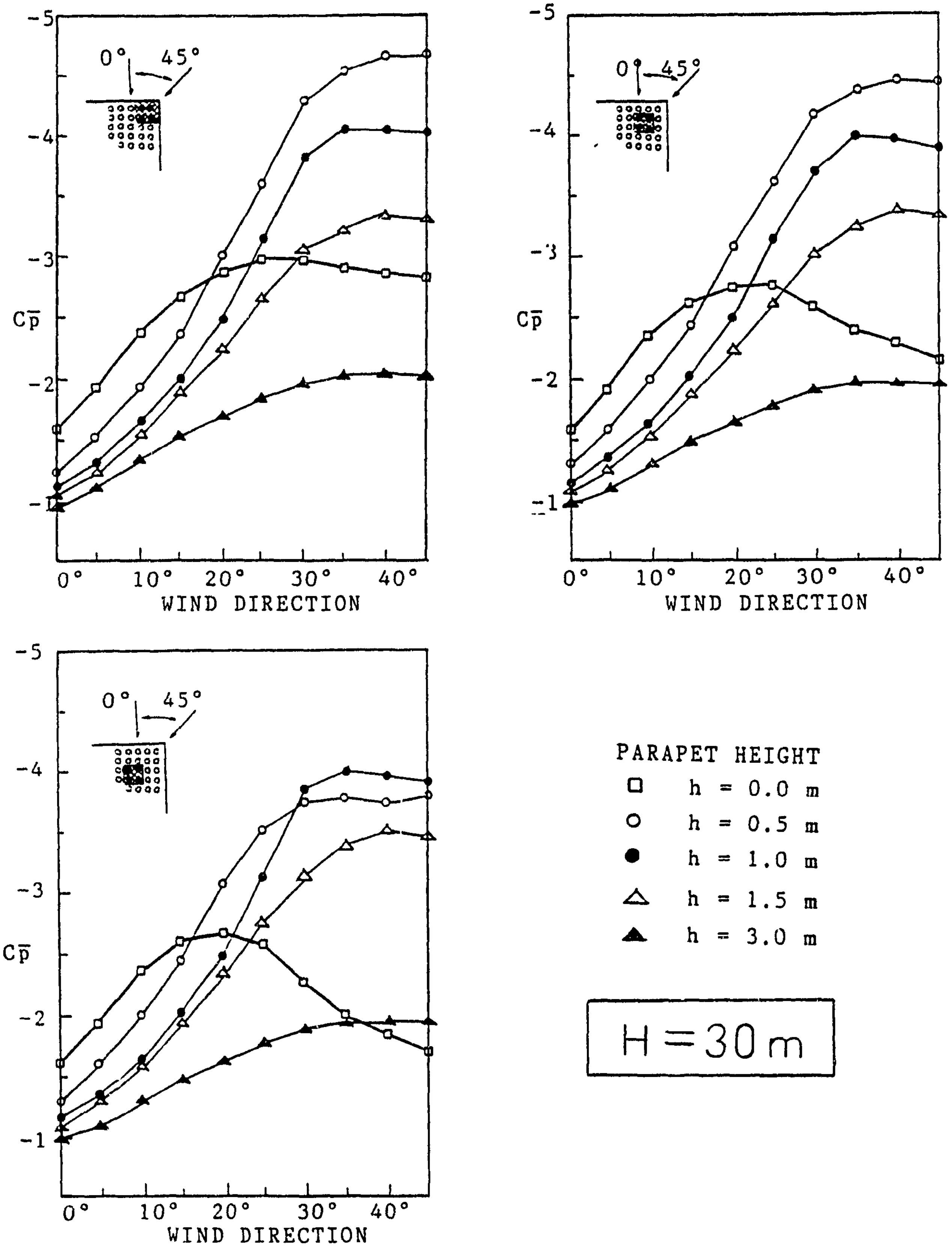


Fig. 4.28 THE EFFECT OF AZIMUTH ON AREA-AVERAGED MEAN PRESSURE COEFFICIENTS FOR H=30m SUBURBAN TERRAIN

Based on these results, it is clear that several load changes occur in the building roof corners equipped with different parapets. The following conclusions could be made:

1.-Roof corner pressure coefficients increase by low parapets (h < = 1m) regardless of building height in either open country or suburban terrain exposure

2.-High parapets (h > 1.5m) may reduce the wind suctions induced on roof corners of intermediate buildings.

# CHAPTER 5

# APPLICATION FOR STANDARDS AND CODES OF PRACTICE

"Code loads are conventional loads"

... M.G.Salvado

This chapter is divided in two sections.

The first one describes the recommendations available in wind standards whereas the second section, following several comparisons with N.B.C.C. (1990) specifications, suggests how the results of the present study could be implemented in practice.

Based on the experimental data and the results' analysis, useful suggestions for wind loading Standards and Codes of Practice are made.

## 5.1. CURRENT PROVISIONS OF WIND STANDARDS

As discussed in Chapter 2, the majority of wind Codes and Standards have no specifications regarding wind loads on roofs with parapets. However, at present, the National Building Code of Canada (1990) provides some recommendations for wind loads on roofs with parapets. These recommendations are shown in Figures 5.1 and 5.2 reproduced from N.B.C.C. (1990).

For low buildings, note (7) in the figure suggests, that for roofs having a perimeter parapet with a height of 1m or greater, the corner coefficients Cp*Cg for small tributary areas can be reduced from -5.4 to -4.4. For tall buildings, note (4) suggests that the values of Cp* can be reduced from -2.3 to -2.0 for roofs with perimeter parapets having heights > 1m. These notes were suggested following Stathopoulos' studies (1986 and 1987), which were carried out in a boundary layer wind tunnel.

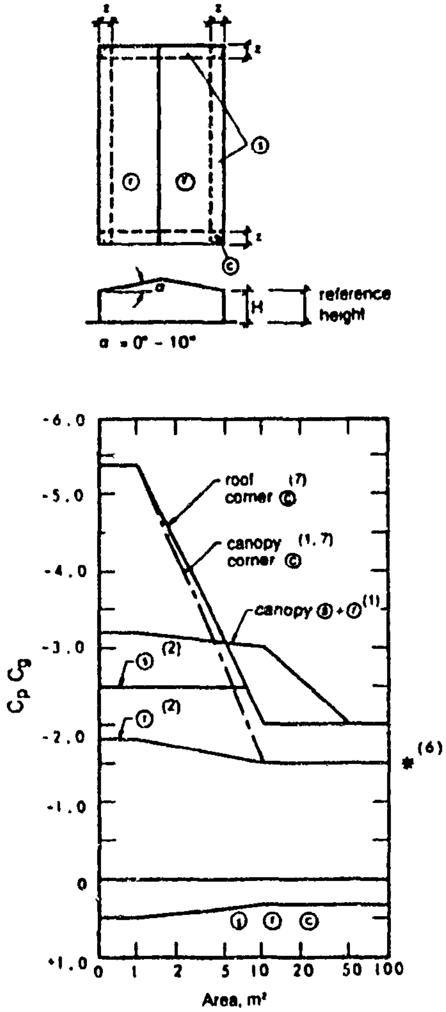
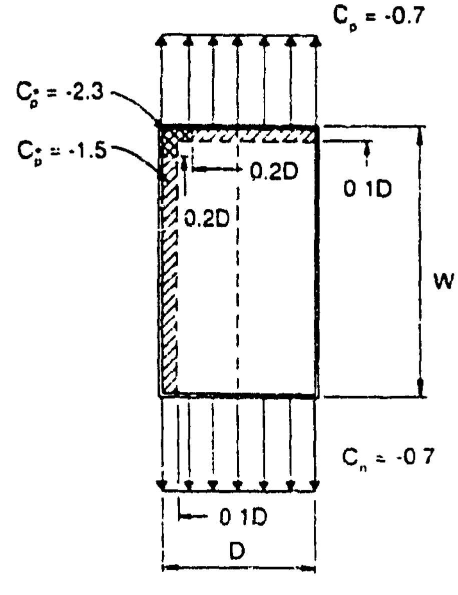


**Figure B-9** External peak pressure coefficients, $C_pC_g$, on roofs of 10° slope or less for design of cladding and secondary structural members

**Notes to Figure B-9:**

(7) For roofs having a perimeter parapet with a height of 1 m or greater, the corner coefficients $C_pC_g$ for small tributary areas can be reduced from −5.4 to −4.4. (30,31)

Fig. 5.1 LOW BUILDING SPECIFICATIONS, AFTER THE SUPPLEMENT OF N.B.C.C. 1990



Plan view of building

| Interior pressures | $C_{pi}$ |
|---|---|
| 1. Openings mainly in windward wall | +0.7 |
| 2. Openings mainly in leeward wall | -0.5 |
| 3. Openings mainly in walls parallel to wind direction | -0.7 |
| 4. Openings uniformly distributed in all 4 walls | -0.3 |

**Figure B-12** End wall pressure coefficients, local suction maxima on the roof and interior pressures for use with Figures B-7 to B-11

**Notes to Figure B-12:**

(4) The value of $C_p^*$ can be reduced from – 2.3 to – 2.0 for roofs with perimeter parapets having heights > 1 m.(30 31)

Fig. 5.2 TALL BUILDING SPECIFICATIONS, AFTER THE SUPPLEMENT OF N.B.C.C. 1990

## 5.2 COMPARISONS WITH N.B.C.C. AND RECOMMENDATIONS

Data from the 10m high building have been compared with low building specifications and results from the 30m height building have been compared with tall building specifications provided by the Supplement to the N.B.C.C. (1990).

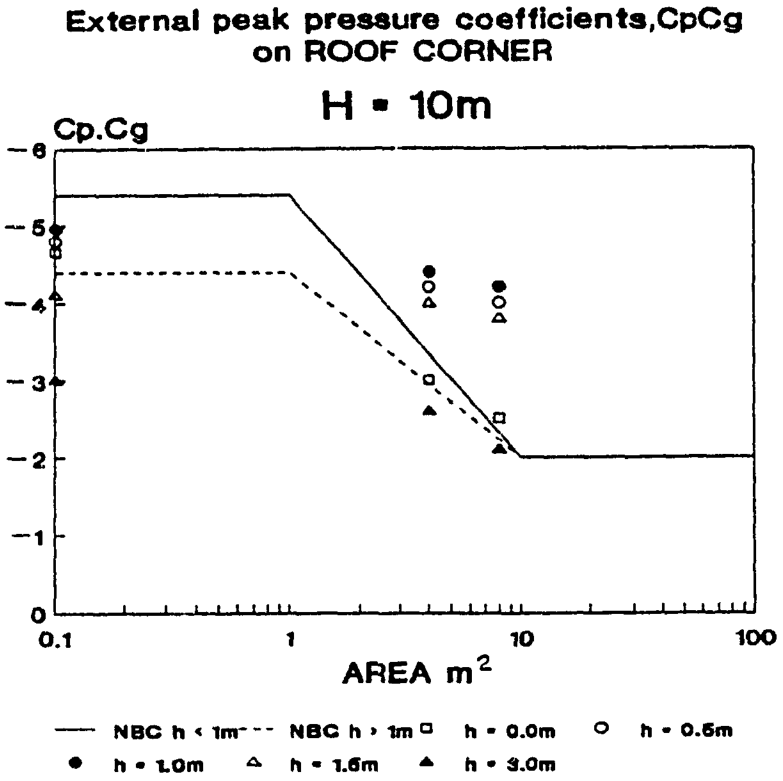
Data are presented in terms of design pressure coefficients, Cp*Cg, for the local and area-averaged most critical values. It should be noted that in the derivation of the Code, these values have been multiplied by a reduction factor equal to 0.8, to arrive to more practical design coefficients. This has been explained by Stathopoulos et al. (1980) and in short it reflects the probability of occurence that the most severe winds, approaching the building from the most critical direction and the most critical combination of building geometry and terrain conditions could all occur simultaneously.

The recommendations for the tall buildings do not provide directly the product Cp*Cg, but Cp and Cg are specified separately. The following table shows the calculations of Cp*Cg for corner areas:

|  | h < = 1m |  | h > 1m |  |
|---|---|---|---|---|
|  | local | area-ave. | local | area-ave. |
| Cp | -2.3 | -2.3 | -2.0 | -2.0 |
| Cg | 2.5 | 2.0 | 2.5 | 2.0 |
| Cp*Cg | -5.75 | -4.6 | -5.0 | -4.0 |

Figure 5.3 (a) compares local and area-averaged pressure coefficients measured on roof corner, for H=10m height building, with those obtained by using the Supplement of the N.B.C.C. (1990). The data show good agreement between the Code and local pressure coefficients measured in the present study. However, one suggestion could be made: the reduction for small tributary areas should be applied just for roofs having the parapet height > 1m (see note 7 of Figure B-9). Also, data show, generally, good agreement between the Code and the area-averaged measured values for no parapet and 3m parapet, while the Code underestimates the measured values for parapet less or equal to 1.5m. The high value measured for parapets lower than 1.5m could be better understood by taking in consideration both the L shape and the proximity to the edge of the tested area where the suctions are very high. Figure 5.3 (b) compares local and area-averaged pressure coefficients measured on the roof edge. The Code somewhat underestimates the measured values for the edge area close to the roof corner.

The experimental data for buildings of intermediate height H=30m were also compared with the provisions of the Code for tall buildings. This comparison is shown in Figure 5.4 for local and area-averaged peak pressure coefficients. The experimental data seem to be consistent with the Code for buildings with no parapet and parapet height greater than 1m, whereas the pressure coefficients



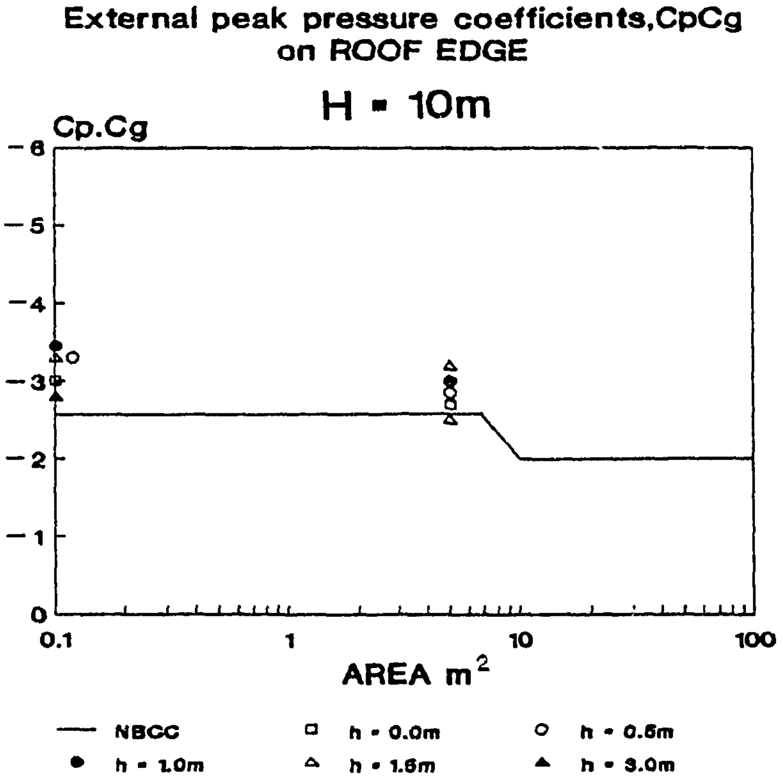


Fig. 5.3 COMPARISON OF MEASURED PEAK PRESSURE COEFFICIENTS AND N.B.C.C. SPECIFICATIONS FOR LOW BUILDING

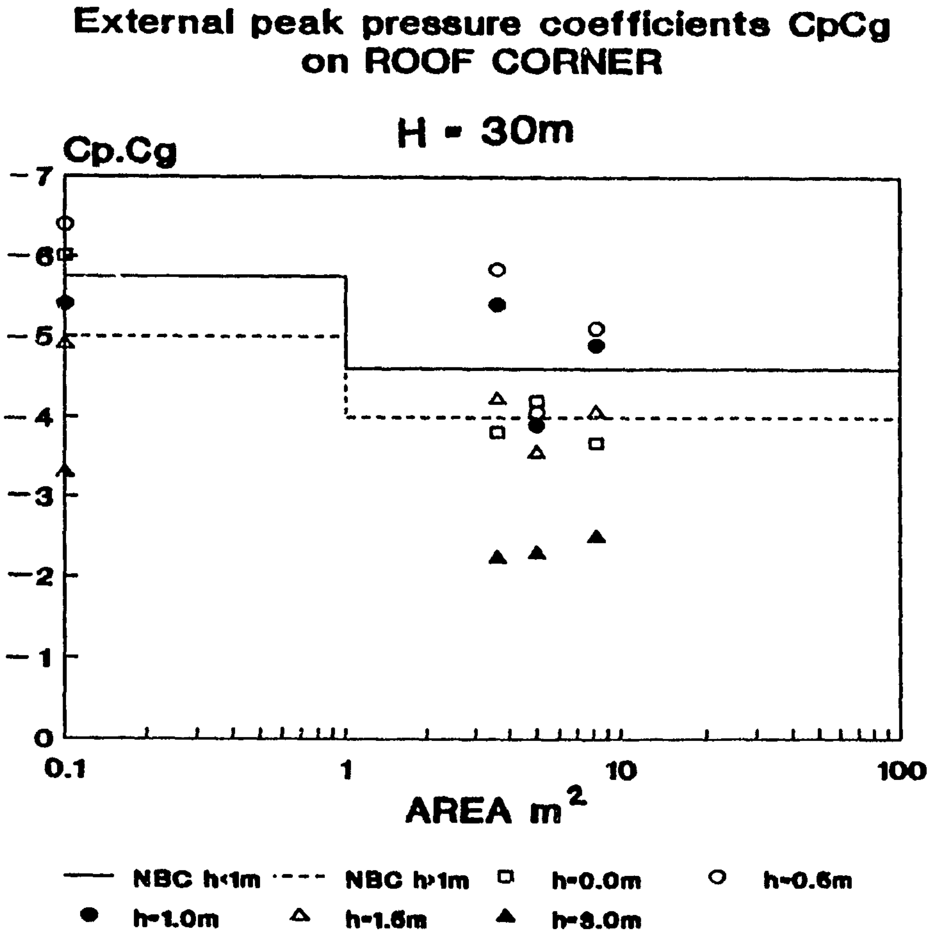


Fig. 5.4 COMPARISON OF MEASURED PEAK PRESSURE COEFFICIENTS AND N.B.C.C. SPECIFICATIONS FOR TALL BUILDING

measured for 0.5m and 1m parapet have higher values than those specified by the Code. Based on the results of the present study, the following recommendations for the effect of parapets on low and intermediate buildings can be made:

LOW BUILDINGS

1.- For roofs having a perimeter parapet with a height of 1m, the local high suctions on roof corners should use the provisions of N.B.C.C. for buildings without parapet

2.- Area-averaged loads acting on roof corners, for small areas situated on the surface covered by the present study (see Figure 3.5), should be increased by 50% for roofs having a perimeter parapet of 1.5m or lower

3.- Local high suctions on roof edges located on the surface investigated by the present study, should be increased by [illegible]0% in the presence of 1.5m and lower parapets, and by 20% in the case of buildings without parapet.

BUILDINGS OF INTERMEDIATE HEIGHT

1.- Local high suctions on roof corners should be increased by 10% in the presence of low parapets (h <1m), for the first zone, as defined in section 4.5.

2.- Area-averaged loads acting on roof corners for small areas placed on the surfaces examined in the present study, should be increased by 20% in the presence of low parapets (h < = 1m).

# CHAPTER 6

## CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

> "At the end of the day, it is important for all concerned to have considered the interactions of the wind and cladding on buildings - ignoring design advice or research results can have dramatic consequences."
>
> ... Eaton, K.J.

A wind tunnel study for the determination of wind loads on flat roof corners with and without parapets has been carried out. The study was experimental and it was performed at the Building Aerodynamics Laboratory of the Center for Building Studies. Models of two buildings with different heights have been examined under various wind directions. Both local and area-averaged pressures have been measured and analyzed for a variety of roof parapets. The assessment of the wind loads has been made under two different terrain conditions, i.e. open country and suburban.

The high density of pressure taps has allowed the detailed investigation of the effect of the distance of tap from the edge of the roof and the effect of the parapets on the pressure coefficients measured.

The experimental results indicate that for all different configurations tested, low parapets generally increase both, mean and peak suctions for low and higher buildings. This increase may be critical if one considers that a low parapet, less than 1m is used in most flat roof buildings.

The influence of parapet on the wind-induced loads on buildings appears to be independent of the terrain roughness. Peak pressure coefficients, however, increase with the increasing terrain roughness, whereas mean values remain, generally, the same.

Parapets with a height of 1.5m or lower will increase these loads in the case of low buildings whereas only parapets with height of 1m or lower will have the same effect in the case of buildings of intermediate height.

A 3m parapet reduces significantly the corner loads for buildings of intermediate height, but only marginally in the case of low buildings.

Some suggestions for Wind Standards and Buildings Codes of Practice based on the results of the present study have been made.

More experimental results are required in order to expand these findings for other building or parapet configurations.

The current state-of-the-art, in this area, can be advanced by studying the wind pressure loads for various roof shapes with parapets and by fixing parapets just around some edges or part of the building roofs.

The wind loads on flat roof corners are increased due to parapets. Therefore, we recommend for the future research the investigation in detail of the entire corner area, in order to have a more complete consideration of this phenomena.

Finally, wind loads on parapet surfaces must be evaluated too, in order to determine whether parapets are economically justifiable as a mean for reduction of wind loads acting on the interior of the building roofs.

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# APPENDIX - 1

# CONTOURS OF MEAN AND PEAK PRESSURE COEFFICIENTS FOR OPEN COUNTRY EXPOSURE WIND DIRECTION $\theta = 30^\circ$

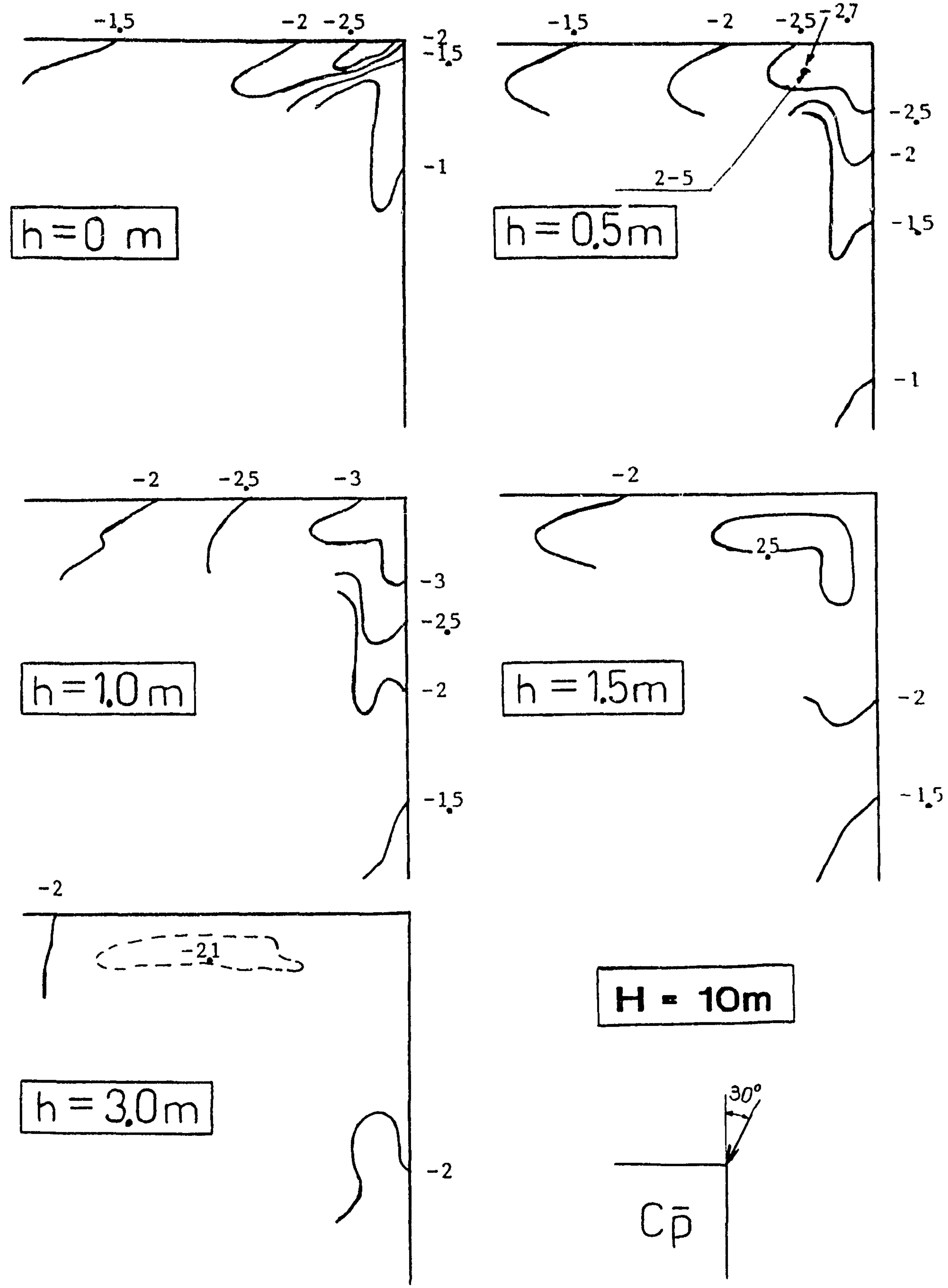

FIG. A1.1 CONTOURS OF MEAN PRESSURE COEFFICIENTS FOR H=10m (OPEN COUNTRY EXPOSURE)

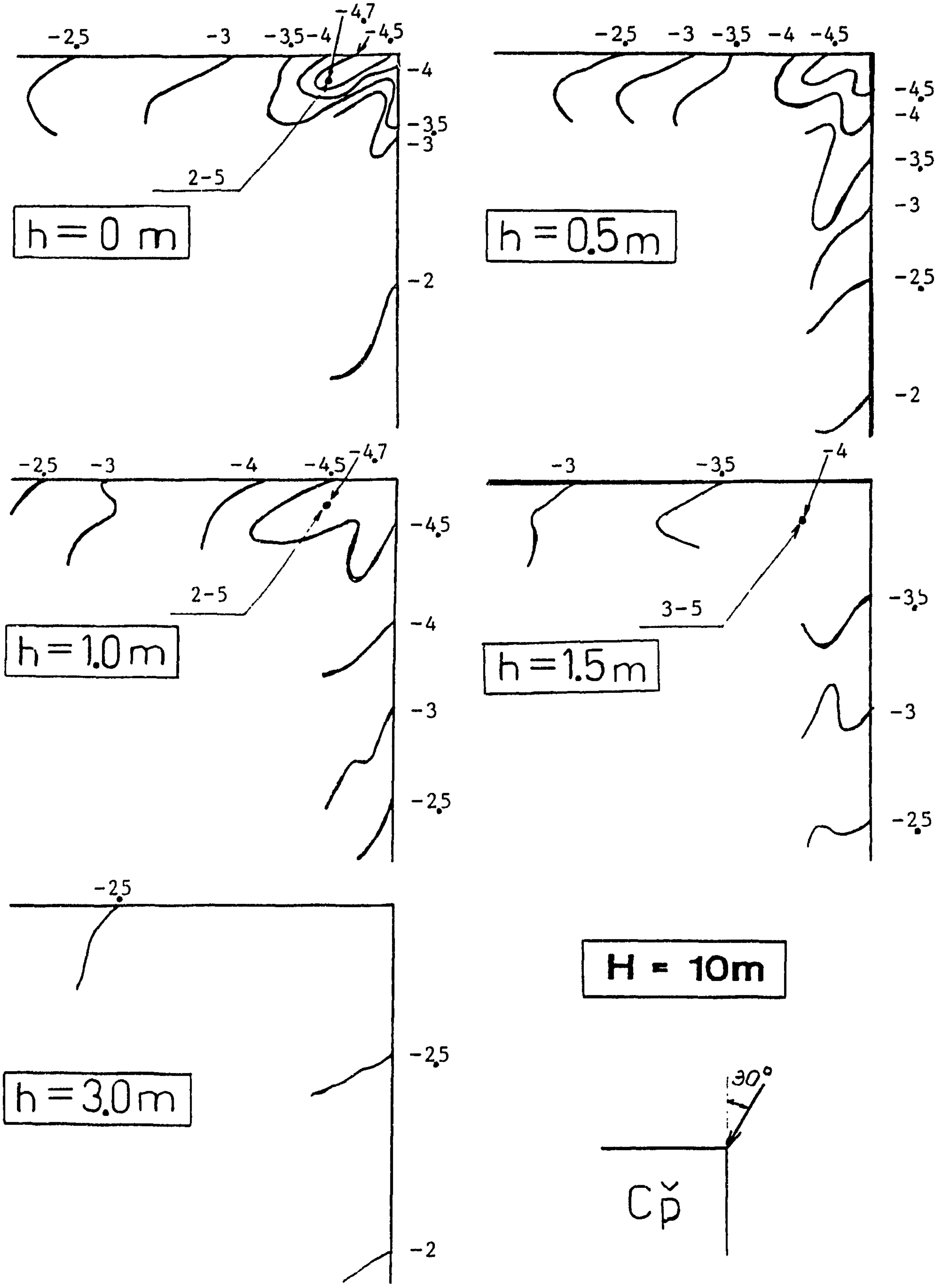

FIG. A1.2 CONTOURS OF PEAK PRESSURE COEFFICIENTS FOR H=10m (OPEN COUNTRY EXPOSURE)

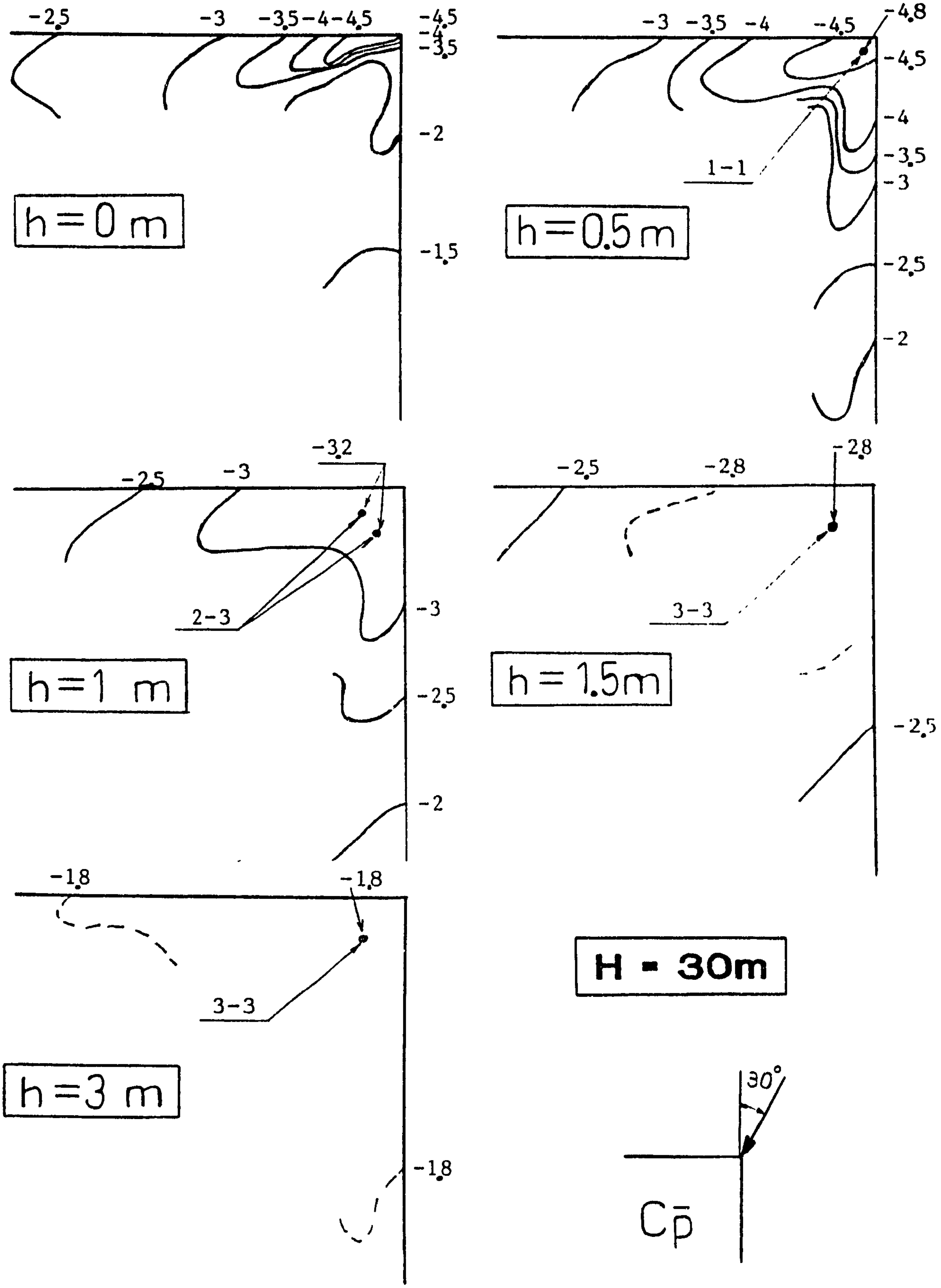

FIG. A1.3 CONTOURS OF MEAN PRESSURE COEFFICIENTS FOR H=30m (OPEN COUNTRY EXPOSURE)

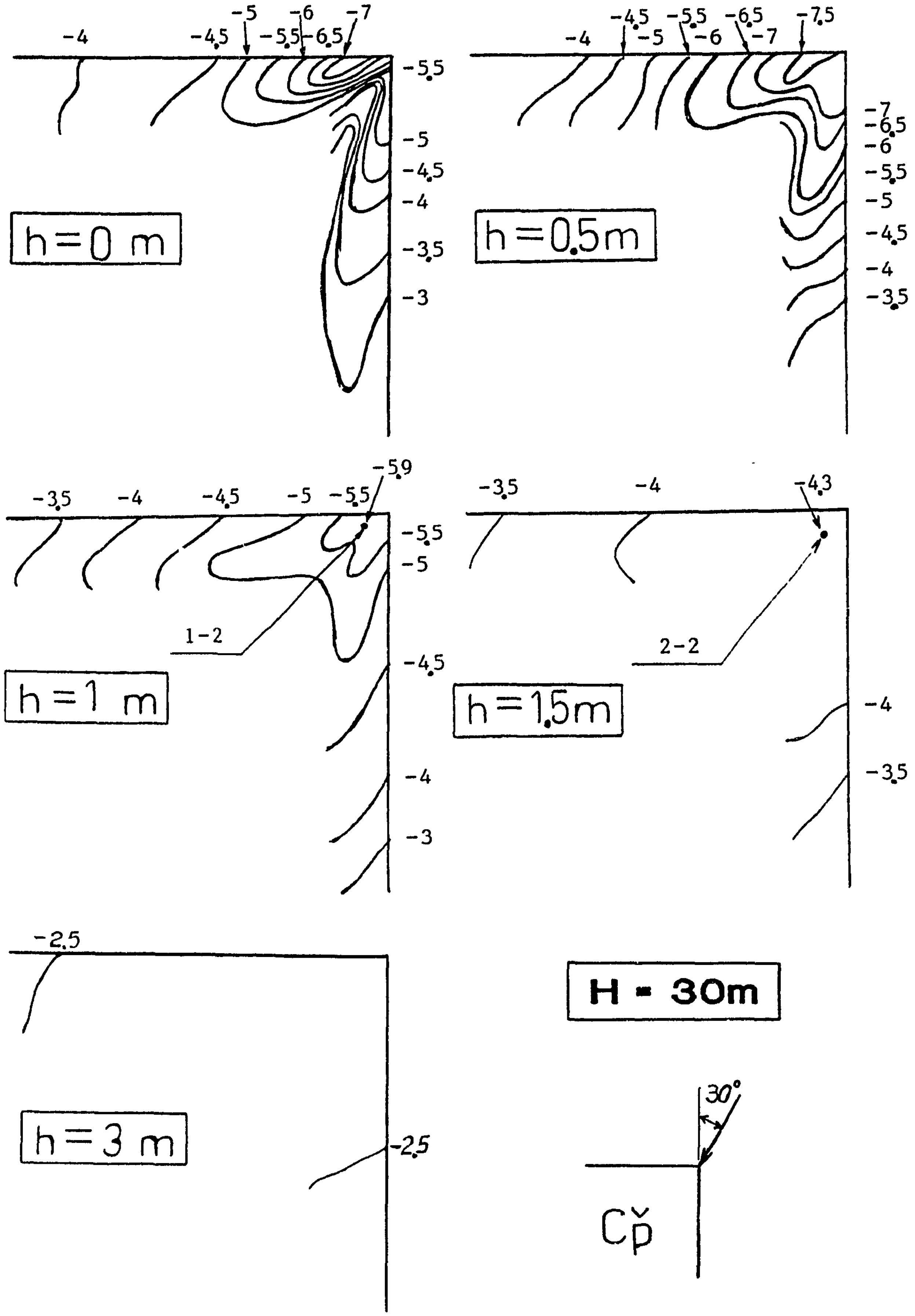

FIG. A1.4 CONTOURS OF PEAK PRESSURE COEFFICIENTS FOR H=30m (OPEN COUNTRY EXPOSURE)