Wind Loads on Flat Roofs with Parapets

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ABSTRACT

WIND LOADS ON FLAT ROOFS WITH PARAPETS

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

The present study has performed a systematic and intensive research to evaluate the wind loads on flat roofs with parapets. The study is experimental and is being carried out in the Building Aerodynamics Laboratory of the Centre for Building Studies. The basic model is a flat roof square building which has been tested in the boundary layer wind tunnel for wind blowing over simulated open country and urban terrains. Mean, peak and root mean square values of wind pressure have been recorded using both local load and area-averaged measurement techniques.

The analysis of the experimental results indicates that for all different configurations tested, parapets generally reduce the high suctions on the roof edges and may only slightly affect the loads acting on the interior areas of the roof. Roof corners, which suffer the majority of

failures, are affected by a significant increase on both mean and peak suctions for all buildings with low parapets. This finding, which has also been confirmed by using extreme value distribution analysis, becomes critical if one considers that a parapet about 0.75 m high is used in most flat-roof buildings. The influence of parapets on the wind-induced loads on buildings appears to be independent of the terrain roughness.

Applying the results in practice reveals that the ANSI Standard specifications for wind loads on buildings with parapets may be inadequate for roof corner areas. Suggestions for Wind Standards and Codes are made.

ACKNOWLEDGEMENT

My gratitude to Dr **Ted.** Stathopoulos for initiating and guiding me **ALL THE WAY** through in completing this project.

I wish to dedicate this thesis to my brother **Mr A. Srinivasan, M.Com, B.Ed.**

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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

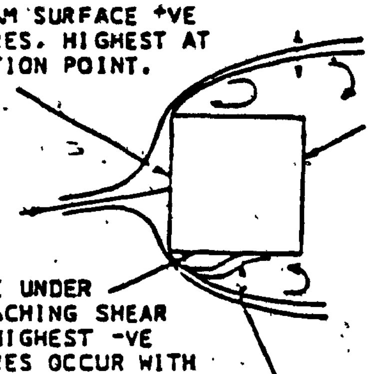
1.1 GENERAL

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. Consequently, unexpected wind forces may act on these structures and, in the limit, damage may occur. The reliable prediction of wind response of buildings still seems to be a challenging task for researchers and scholars.

Fortunately, complete destruction of buildings or structures by the wind is actually rather rare; but local failures, especially to the roofs and claddings elements, are more common and they are much costly. 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 wind loadings.

Wind loading on roofs is a complex problem. Therefore a closer view to the wind loading mechanism seems to be necessary. Figure 1.1 shows a bluff body in a turbulent flow (26). Different pressure regions are clearly identified and explained. The highest compression is found at the stagnation point of the front face. Generally, the pressure distribution over the building envelope is not constant and the maximum negative pressure appears near the leading roof edge from where the flow separates and reattaches further down the roof. This high suction may cause many structural failures on roof claddings. As a result, several investigations have been made on this topic.

In 1975, Melbourne (26) developed a hypothesis on the cause of high suctions occuring near the leading edge and this is presented in Fig 1.2. A very low, intermittent pressure was found on the surface under the shear layer near the leading edge. Any decrease in the pressure will

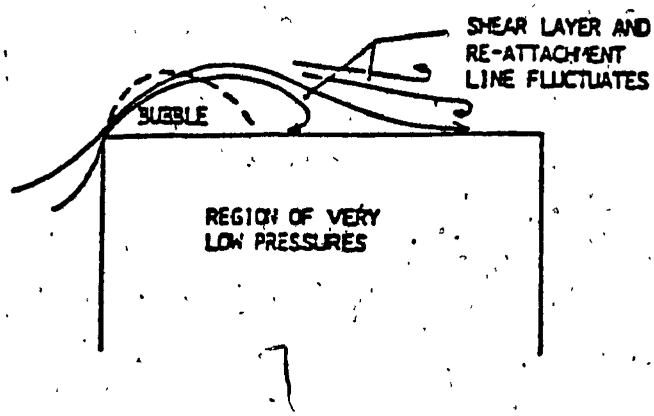


(A) THE UPSTREAM FACE WHERE THE MEAN PRESSURES ARE POSITIVE. THE RMS PRESSURE FLUCTUATIONS ARE CAUSED PRIMARILY BY THE LONGITUDINAL VELOCITY FLUCTUATIONS OF THE INCIDENT TURBULENCE, WHICH ARE APPROXIMATELY NORMALLY DISTRIBUTED.

(B) THE STREAMWISE FACES (INCLUDING ROOFS) NEAR AN UPSTREAM CORNER, IN PARTICULAR UNDER INTERMITTENTLY RE-ATTACHING SHEAR LAYERS, ARE WHERE THE HIGHEST NEGATIVE SURFACE PRESSURES OCCUR. THE PRESSURE FLUCTUATIONS IN THESE AREAS CAN BE FAR FROM NORMALLY DISTRIBUTED AND ARE RELATED TO THE LOCAL RADIUS OF CURVATURE OF THE FLUCTUATING SHEAR LAYERS.

(C) THE REAR FACES WELL DOWNSTREAM OF ANY RE-ATTACHMENT IN THE WAKE OR UNDER A FULLY SEPARATED SHEAR LAYER WHERE THE PRESSURES ARE NEGATIVE. THE RMS PRESSURE FLUCTUATIONS RELATE TO TOTAL WAKE PRESSURE FLUCTUATIONS AND ARE RELATIVELY LOW WITH DISTRIBUTIONS SHOWING MODERATE INTERMITTENCY. THE PRESSURES IN THESE AREAS ARE NOT NORMALLY CRITICAL FOR CLADDING DESIGN.

FIG. 1.1 TURBULENT FLOW AROUND A BLUFF BODY (26)



1. SHEAR LAYER RE-ATTACHMENT EFFECTIVELY SEALS OFF BUBBLE FROM DIRECT VENTING TO FREESTREAM.
2. FREESTREAM FLOW OVER THE FRONT OF THE SHEAR LAYER ACCELERATES. THE INCREASED VELOCITY IS ACCOMPANIED BY A DECREASE IN PRESSURE.
3. THE COMBINED EFFECTS OF ENTRAINMENT INTO THE SHEAR LAYER FROM INSIDE THE BUBBLE AND THE DECREASE OF PRESSURE AT THE BOUNDARY CAUSES THE SHEAR LAYER TO MOVE TO REDUCE BUBBLE VOLUME AND INTERNAL PRESSURE (DOTTED LINE).
4. THIS PROCESS CONTINUES IN AN UNSTABLE WAY TO REDUCE SURFACE PRESSURES UNDER THE BUBBLE UNTIL IT IS VENTED BY BURSTING OR BY ARTIFICIAL MEANS.

FIG. 1.2 WIND-INDUCED SUCTIONS ON FLAT ROOFS(26) cause the initial radius of curvature of the shear layer to decrease and the peak negative pressure could be reduced substantially if the bubble around the re-attaching shear layer were vented.

Some past works (17, 18, 20, et al.,) have also found that roof covering elements and various architectrual features have their unique significant effects on the roof wind loadings. One of such 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. Plate 1.1 shows a group of buildings in New York city. A close view of that picture leads to an estimate that around 80 % of buildings have parapets on their roofs. However, the wind effects induced on roofs, 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

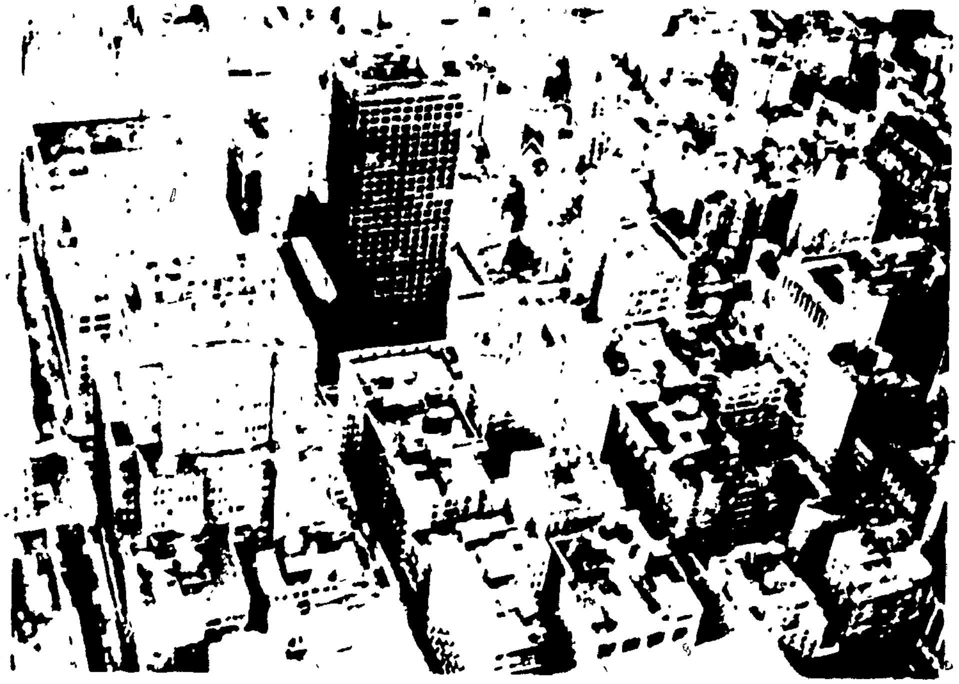


PLATE1.1 BUILDING ROOFS WITH PARAPETS

building configurations are quite interesting to estimate.

All Building Codes of Practice have some specifications for wind loads on roofs without parapets. Wind loads on roofs with parapets are not specified in any building code. The present study attempts to evaluate the effect of parapets on wind pressures acting on flat roofs. Different building heights are examined under the influence of many directions of wind. The assessment of wind loads under different exposure conditions has also been attempted. Based on the experimental results, some recommendations for roof 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 discuss the results of the experimental study. For convenience, the various data are presented under four different headings, dealing with: the general overall effects of parapets on roof; the parapet-induced wind effects on the interior areas of the roof; the variation of the wind loads for roof edges due to parapets; and the detailed study of the roof corner wind loading.

The quality assurance of peak pressure coefficients measured in the wind tunnel is discussed in the Chapter 5 by using extreme value distribution analysis. In Chapter 6, the application of present study results to the Wind Standards and Codes of Practice are presented. Finally, the conclusions and recommendations for further research in this topic are suggested in Chapter 7.

CHAPTER 2

LITERATURE REVIEW

" Past experience has significant influence in the present achievements "

....A.G. DAVENPORT

2.1. DESCRIPTION OF THE EXISTING WORK

Only a limited number of studies were made in the past for 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 (22), two decades ago in a wind tunnel of the aeronautical type. 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 this 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.

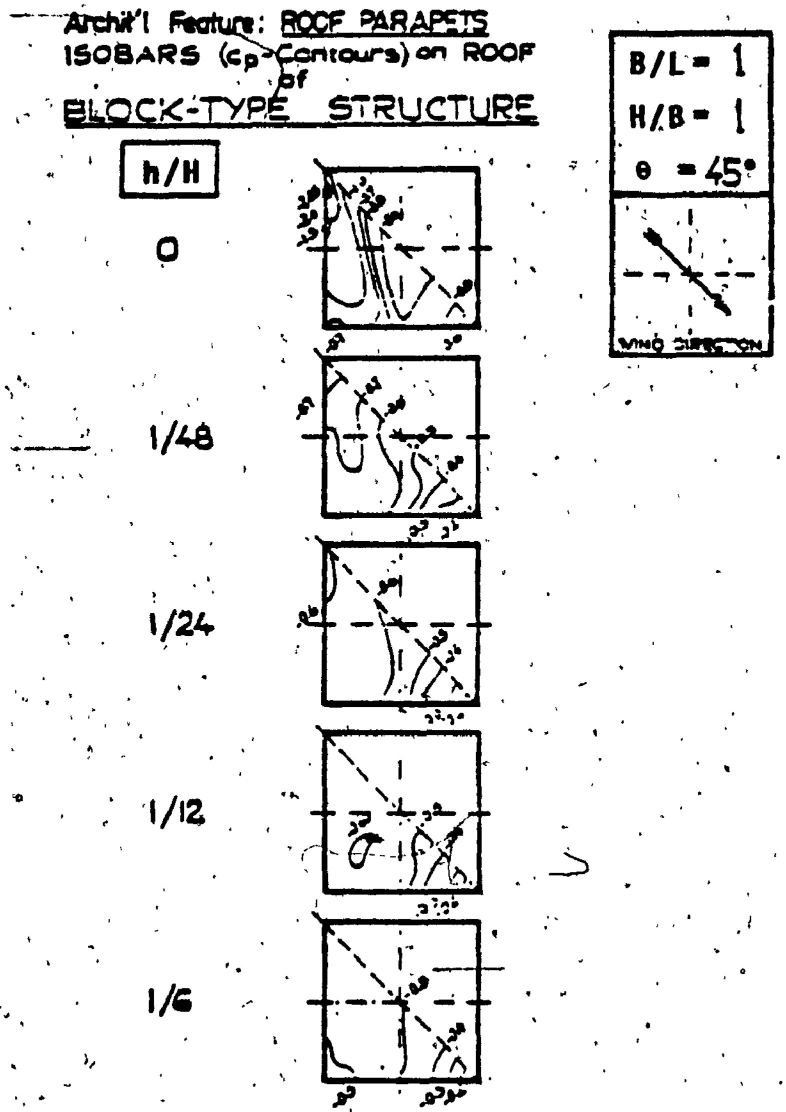


FIG. 2.1 EFFECTS OF PARAPETS ON ROOF PRESSURE DISTRIBUTION FOR CORNERING WIND (22)

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/ZØ (height of the building / roughness length) was neglected by this study. Thus the above results may not be representative if one considers the actual turbulent flow conditions of the natural wind.

Columbus (5) carried out various tests both in uniform and turbulent flow conditions for the same building configurations that Leutheusser (22) 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 (9) have tested the effects of parapet on low-rise building models in a boundary layer wind tunnel. They concluded that local mean suctions become worse when parapets are added, in particular for cornering wind. Castellated parapets, although better than regular parapets, cause only limited load the reductions.

Kramer et al. (21) 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 (37), 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 systematic approach followed by Stathopoulos(38) gives 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.

The review of the existing knowledge will be completed with the recent work from the University of Western Ontario, carried out by Lythe and Surry (24). The study had two main objectives; first, to determine the general distribution of wind loads on flat roofs and secondly, to evaluate the effects that parapets have on these loads. The conclusions of this work may be summarized as follows:

1) Parapets increase the interior peak pressure for low buildings but decrease them for high buildings. Mean pressures are little affected by parapets.

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

3) 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.

2.2 JUSTIFICATION OF THE PRESENT STUDY

Wind Standards and Codes of Practice have no information regarding the effects of wind on flat roofs with parapets, as previously mentioned. Not much attention has been paid on the wind loads acting on tall building roofs with parapets and the limited number of existing studies do not seem to yield concurrent results.

According to Stathopoulos (38), parapets increase the corner roof wind loads significantly. Therefore, a comparison of the local mean wind loads for the corner regions of various existing studies has been attempted. Figure 2.2 shows on the top, the comparison between the studies of Lythe and Surry (24) and Kramer et al. (21), for different H/B ratios tested. When the aspect ratio is more than 0.5, ie for taller buildings, disagreement is quite high. In the bottom part of Fig. 2.2 results are compared for various parapets used in previous experimental (21,37) works. Again the mean pressure coefficients do not seem to agree well. In fact the disagreement among these studies is much higher than what small differences in model geometry could explain.

The study of Lythe and Surry (24) describes the effects of parapets on roof wind loading for buildings of different heights. Wind pressures for roofs having parapets 1.3 m and above have been measured. In practice, however, most of the flat roofs are fitted with parapets less than or around 1.0 m. So the present study attempts to in evaluate the roof wind loads also for parapets less than 1.0 m high. Lythe and Surry (24) have tested only two wind directions (0°,45°). However, in order to get the most critical pressure coefficients, additional wind directions (30°, 60°, 90°) are added in the present work. The pressure tap locations are made closer to the edges than the previous studies, to predict the most critical edge wind loadings.

In addition, to understand the behaviour of the corner wind loads, in detailed manner, spectral analysis has been used.

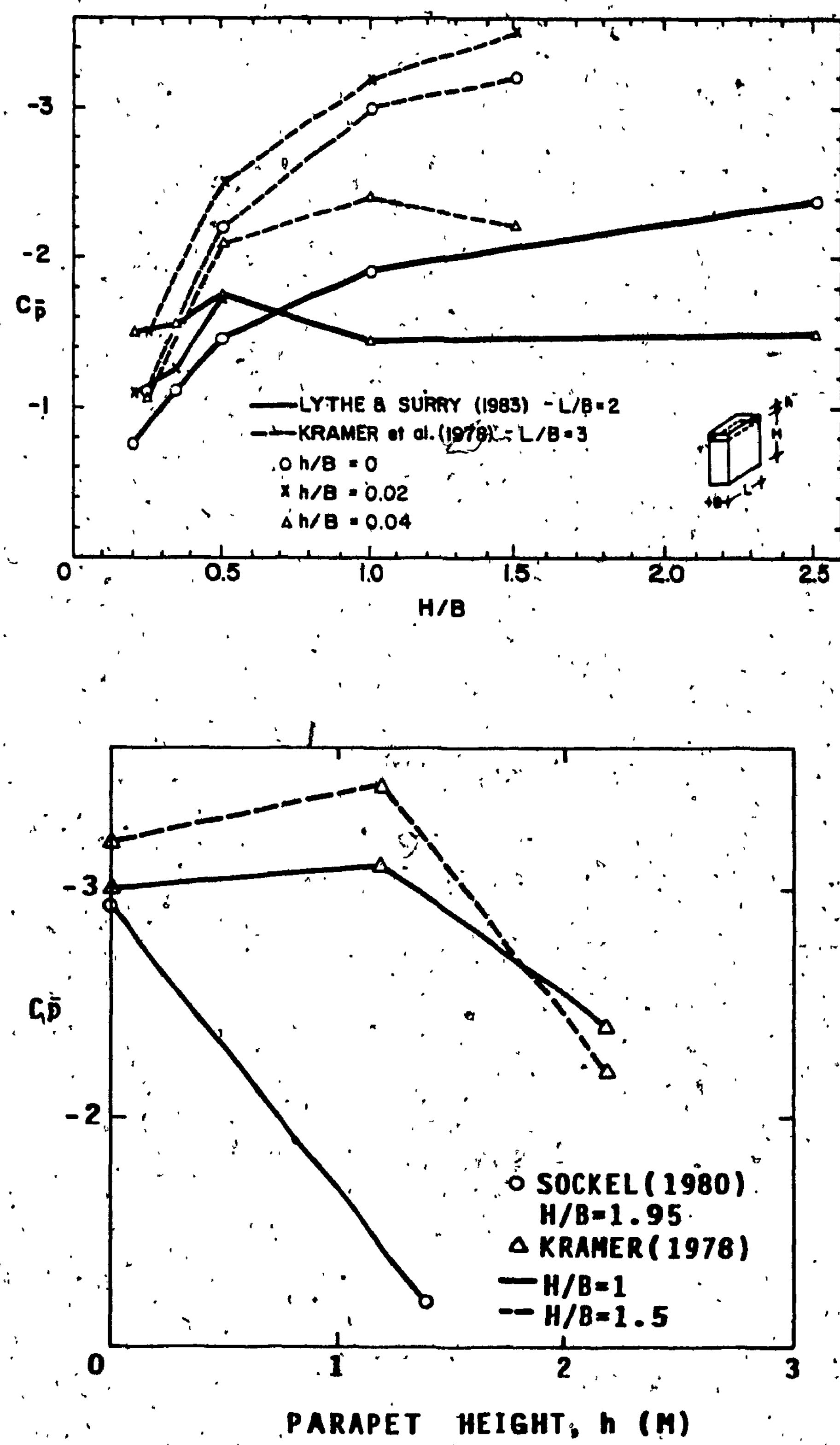


FIG. 2.2 DATA FROM PREVIOUS STUDIES ON THE EFFECT OF PARAPETS ON ROOFS

For the roof corners peak values of wind pressure fluctuations have been estimated not only from a single recorded but also from a detailed extreme value analysis of measured peaks. The present experimental work also includes the effect of parapets on wind induced area-averaged pressures and the influence of two different terrains (open country - urban) on the wind load assessment.

Virtually, this thesis is dedicated to the design wind loads on flat roofs with parapets on taller buildings. The urgent need of this work has also been indicated by Saffir (33) as follows:

" The results of **Stathopoulos's** experimental study and report on wind pressure on low buildings with parapets are very valuable. Unfortunately, very little data is available on the effects of parapets for high-rise buildings, where suction loadings on the roof corners may be extremely high. It would be desirable to determine the effects of parapets on high-rise buildings by additional experimental study. "

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 twenty - five 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 modeling 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 this phenomenon was undertaken by Schlichting in his fundamental work (35). The boundary layer can 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 Fig. 3.1 the boundary layer on a smooth plate can 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

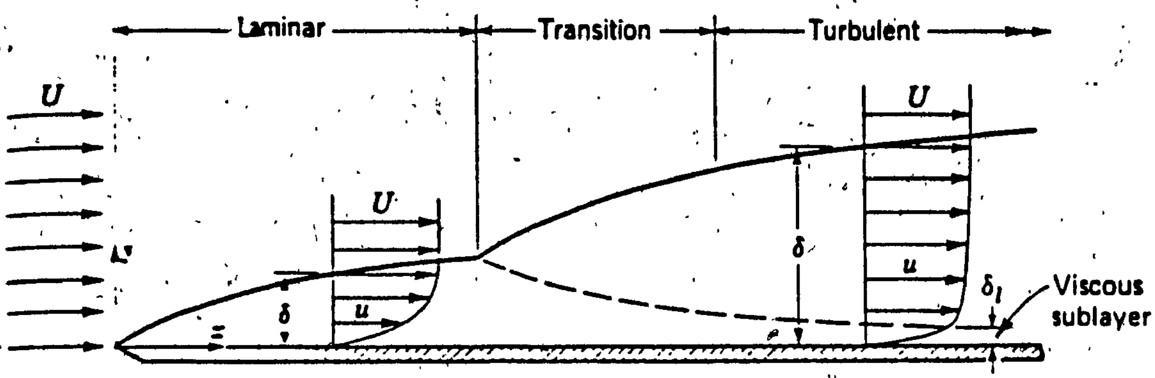


FIG. 3.1 LAMINAR AND TURBULENT BOUNDARY LAYERS ALONG A SMOOTH FLAT PLATE- VERTICAL SCALE EXAGGERATED (11)

characteristics with those of natural wind near the ground surface.

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 condition shown in the top picture represents exposure A as per National Building Code of Canada (NBCC) or exposure C as per the American Standard (ANSI). The urban terrain may correspond to exposure C of the NBCC or exposure A of ANSI Standard. Here for the open country terrain the boundary layer develops over the roughness of a carpet. For the urban exposure eggbox panels have been placed on the top of the carpet. The eggboxes were stapled in different positions to create the necessary roughness to yield the required turbulence at the centre of the turntable, where the model locates.

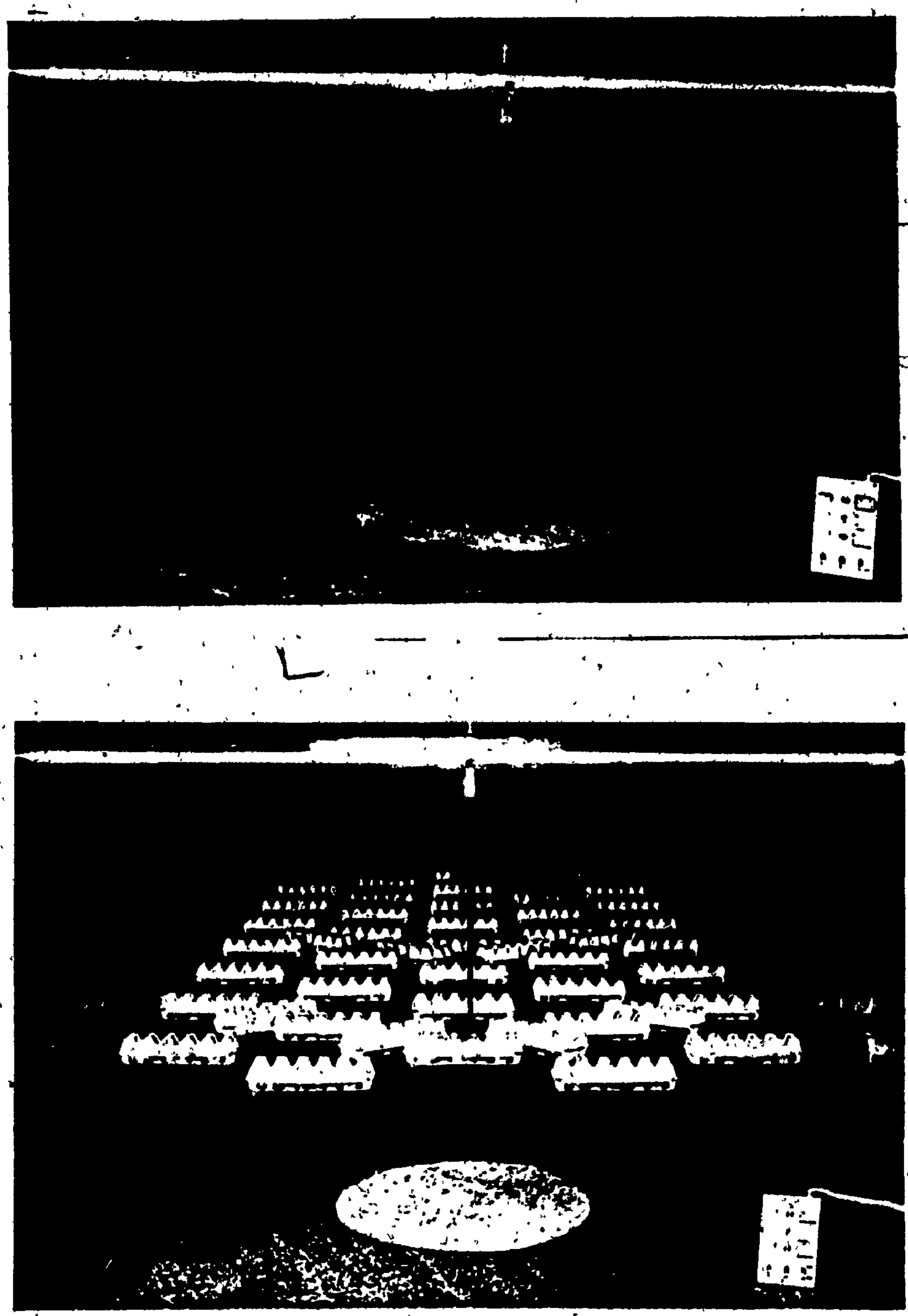


PLATE. 3.1 INSIDE VIEW OF THE TUNNEL IN SIMULATED OPEN COUNTRY AND URBAN TERRAIN

The vertical distribution of the mean velocity and the longitudinal turbulence intensity for the two simulated flow conditions are shown in Fig. 3.2. It can be noted that for the same terrain roughness the turbulence intensity decreases with the increase of height above ground, and that for the same height, the turbulence intensity increases with the increase of terrain roughness.

By using a power law equation of the form:

$$(V/VG) = (Z/ZG)^{\alpha} \qquad 3.1$$

The best fitted velocity profiles exponent may be estimated as 0.15 and 0.37 for the open country and urban terrain conditions respectively. Experimental values are also fitted by using a logarithimic law equation of the form :

$$V/VG = (1/k)\ Cg\ In(Z/Zo) \qquad 3.2$$

and the various parameters are 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, once the spectral curve of longitudinal turbulence is established. Spectra measurements were thus performed for both open country and urban simulated flow conditions. Figure 3.3

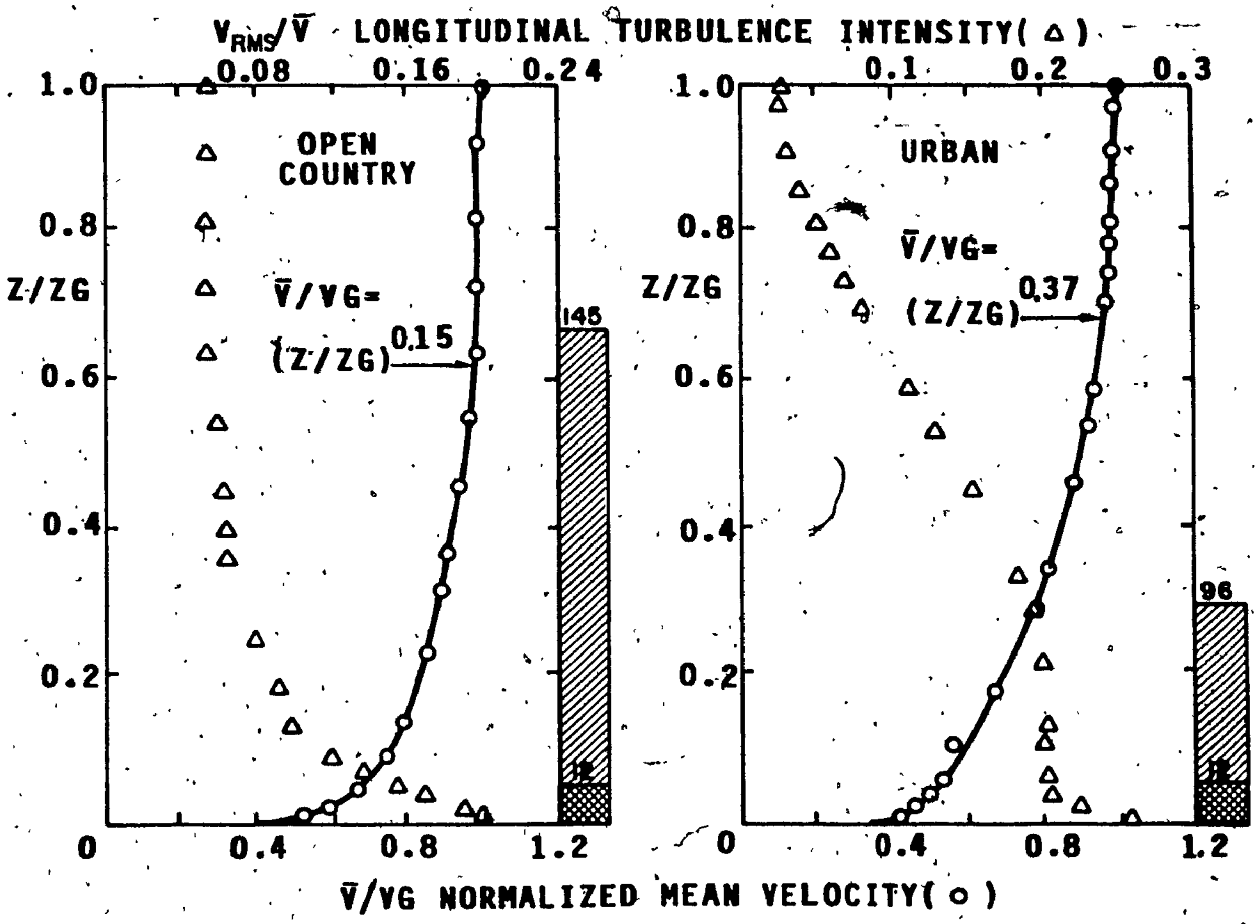


FIG. 3.2 MEAN SPEED AND TURBULENCE INTENSITY PROFILES FOR OPEN COUNTRY AND URBAN SIMULATED TERRAIN EXPOSURES

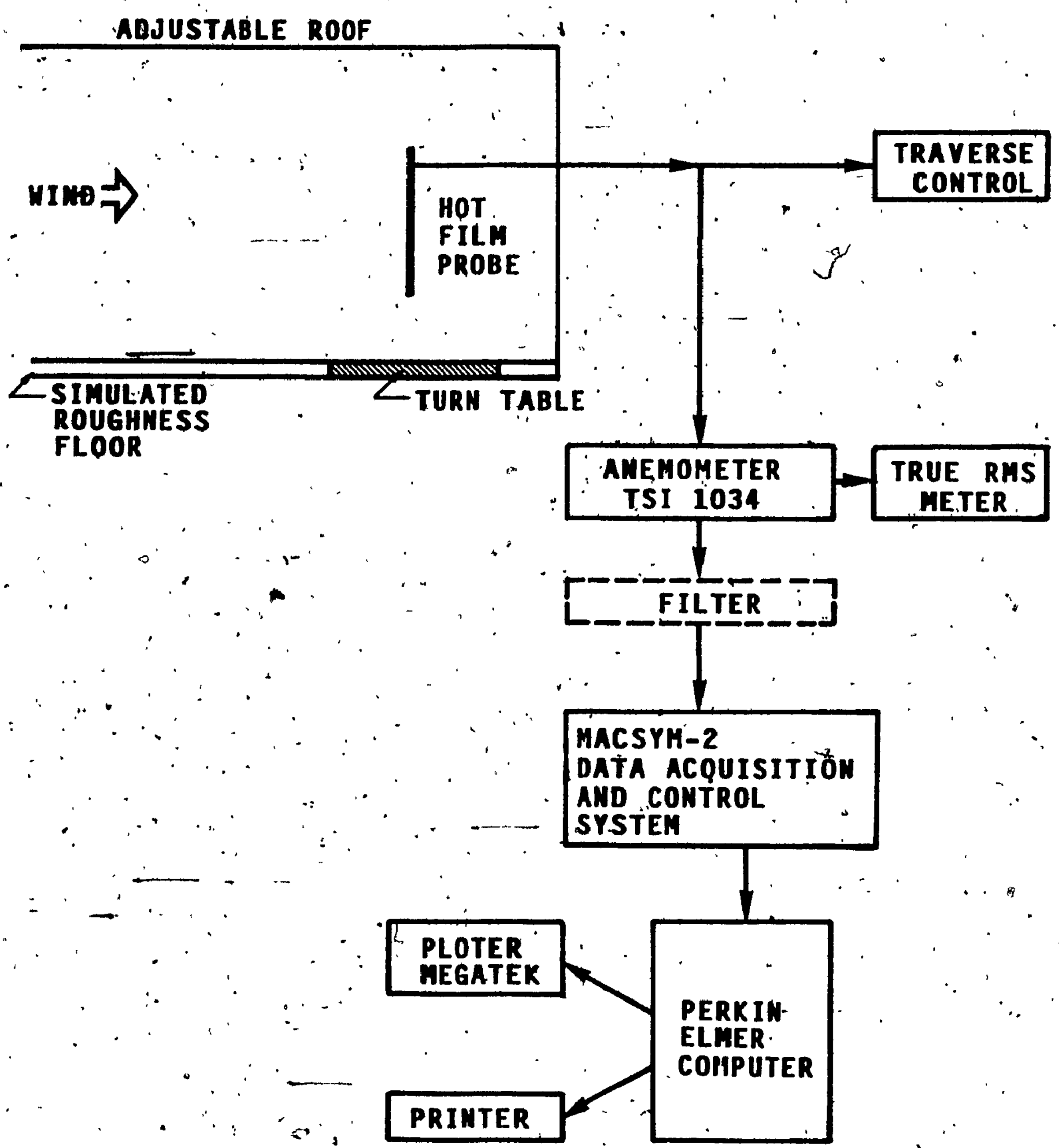


FIG. 3.3 EXPERIMENTAL SETUP FOR SPECTRA MEASUREMENTS

shows diagrammatically the procedure followed for the spectral measurements. The Fast Fourier Transformation (FFT) method was used for the development of spectral estimates. The various experimental parameters used in collecting and analysing these spectra are given in reference 25. Typical spectra measured at Z/ZG = 1/4 are presented for both exposures in Fig. 3.4.

Attempts have been made to compare the experimental data with some of the following empirical and analytical representations (39), such as Davenport's empirical equation:

$$\frac{n\,S(n)}{\sigma^2} = \frac{2}{3}\,\frac{x^2}{(1+x^2)^{4/3}} \quad \ldots \qquad 3.3$$

$$\text{where,}\quad x = \frac{n}{\overline{V}_{10}}\,1200 = \frac{n}{\overline{V}_z}\,\frac{\overline{V}_z}{\overline{V}_{10}}\,1200$$

and Von-Karman's analytical expression:

$$\frac{n\,S}{\sigma^2} = \frac{4x}{(1+70.8x^2)^{5/6}} \quad \ldots \qquad 3.4$$

$$\text{where,}\quad x = \frac{nL_x}{\overline{V}_z}$$

Figure 3.4 shows that there is quite satisfactory agreement between the experimental and Davenport's empirical curve. Results also agree with some field measurements (10). To determine the length scale of turbulence in the longitudinal direction, Von-Karman's analytical model was used (39):

$$L_x = \frac{25\,(Z-d)^{0.35}}{Z_o^{0.063}} \quad \ldots \qquad 3.5$$

The most appropriate parameters of the wind tunnel flow

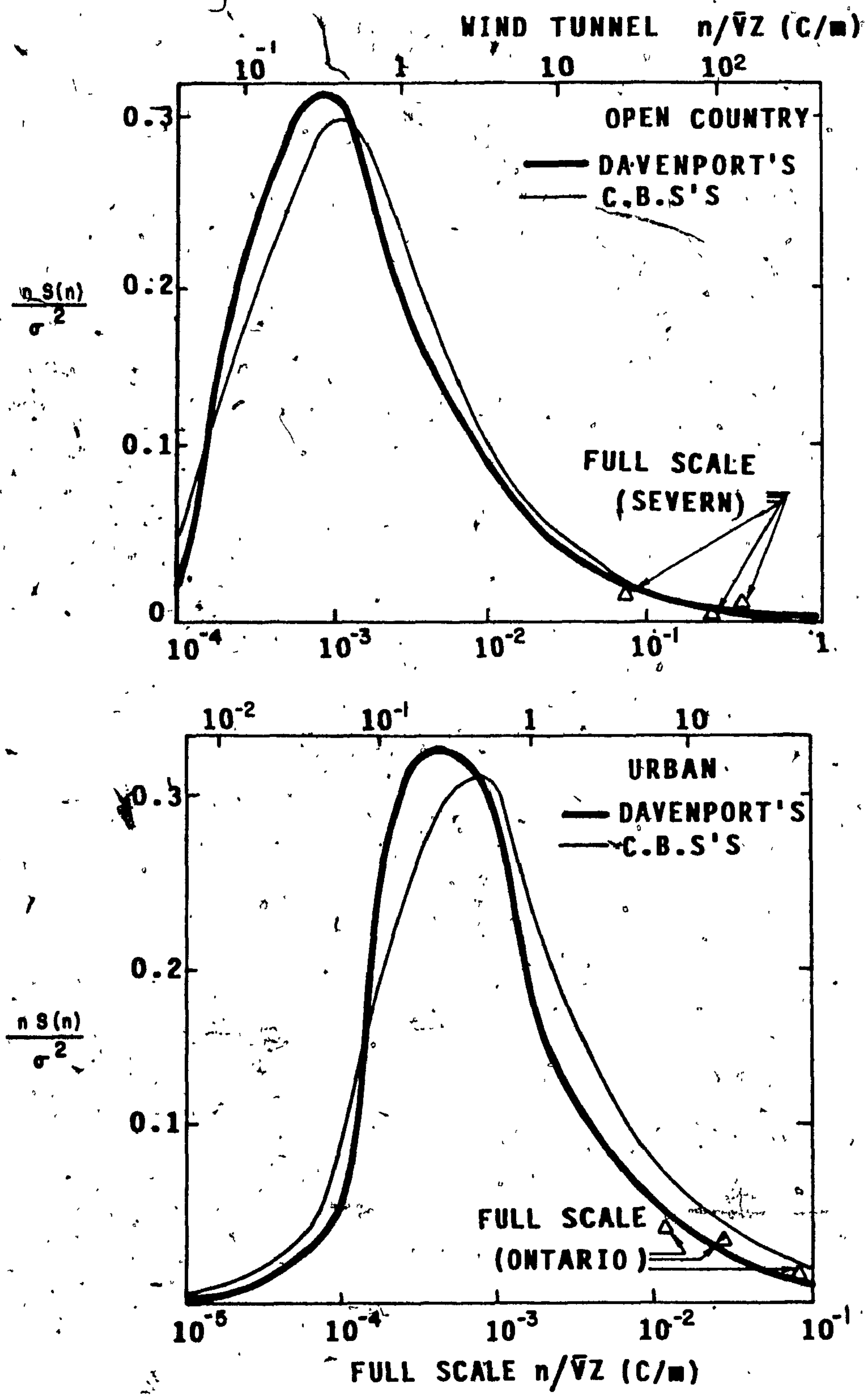


FIG. 3.4 SPECTRA OF LONGITUDINAL TURBULENCE COMPONENT AT Z/ZG=1/4

regime are given in Table 3.1, along with some full scale values which are taken from references 7 and 10. 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 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 (9,48). More information about the simulation characteristics and the design and fabrication of the C. B. S's wind tunnel can be found in reference 39.

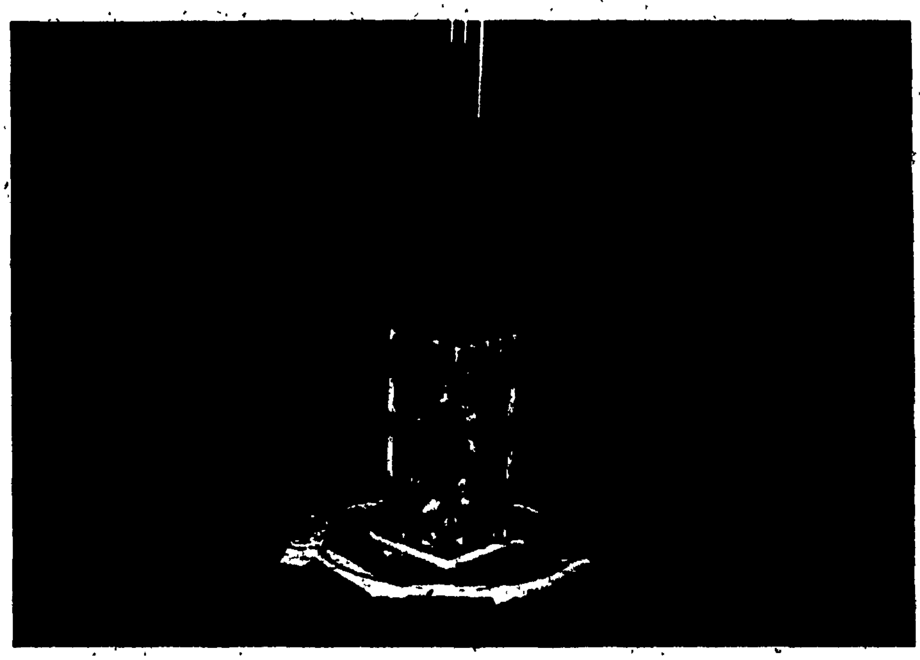
3.3 VARIOUS CONFIGURATIONS TESTED

The basic model used in the present study represents a flat - roofed square building 61m x 61 m, in plan. The model is made of plexiglass and it has been tested with and without parapets, in simulated open country and urban terrain exposures. Plates 3.2 and 3.3 show the model in open country and urban exposure respectively. Both conventional [local load] and area-averaged measurements have been carried out. The pneumatic averaging technique (46) has been used for the measurement of area-averaged pressures.

Figure 3.5 shows the various heights of buildings tested

	FULL SCALE		WIND TUNNEL	
	OPEN COUNTRY	URBAN	OPEN COUNTRY	URBAN
ZG(m)	220-270	450-510	0.58	0.85
Z0(m)	0.001-0.20	1-4	0.0001	0.009
α	0.16	0.40	0.15	0.37
Cg	0.042	0.046	0.042	0.046
LX(m)	75-107	25-117	0.18	0.25

TABLE. 3.1 PARAMETERS FOR FULL SCALE AND SIMULATED FLOW CONDITIONS



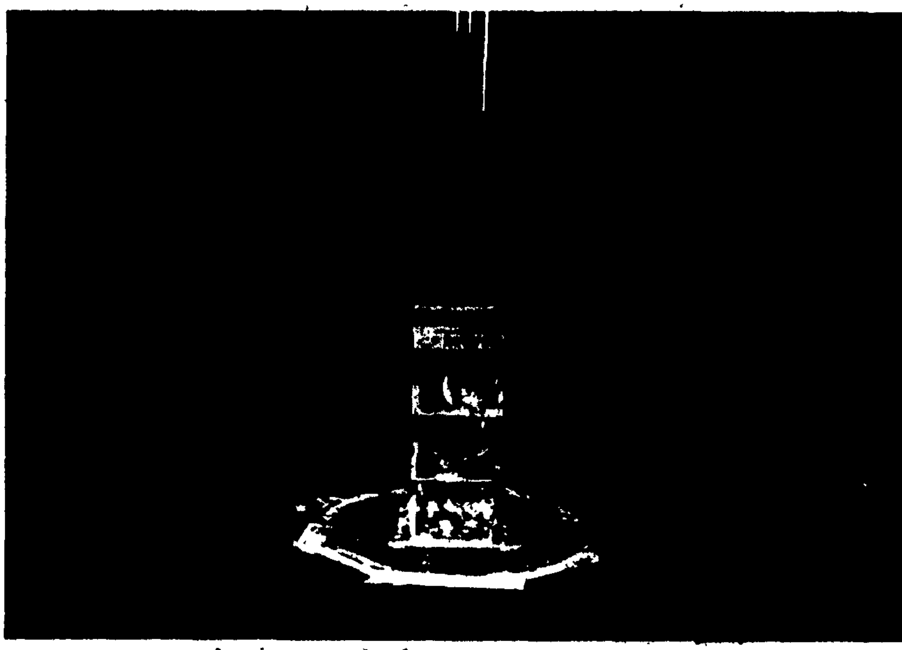


PLATE 3.2 BUILDING MODEL WITH AND WITHOUT PARAPETS IN OPEN COUNTRY

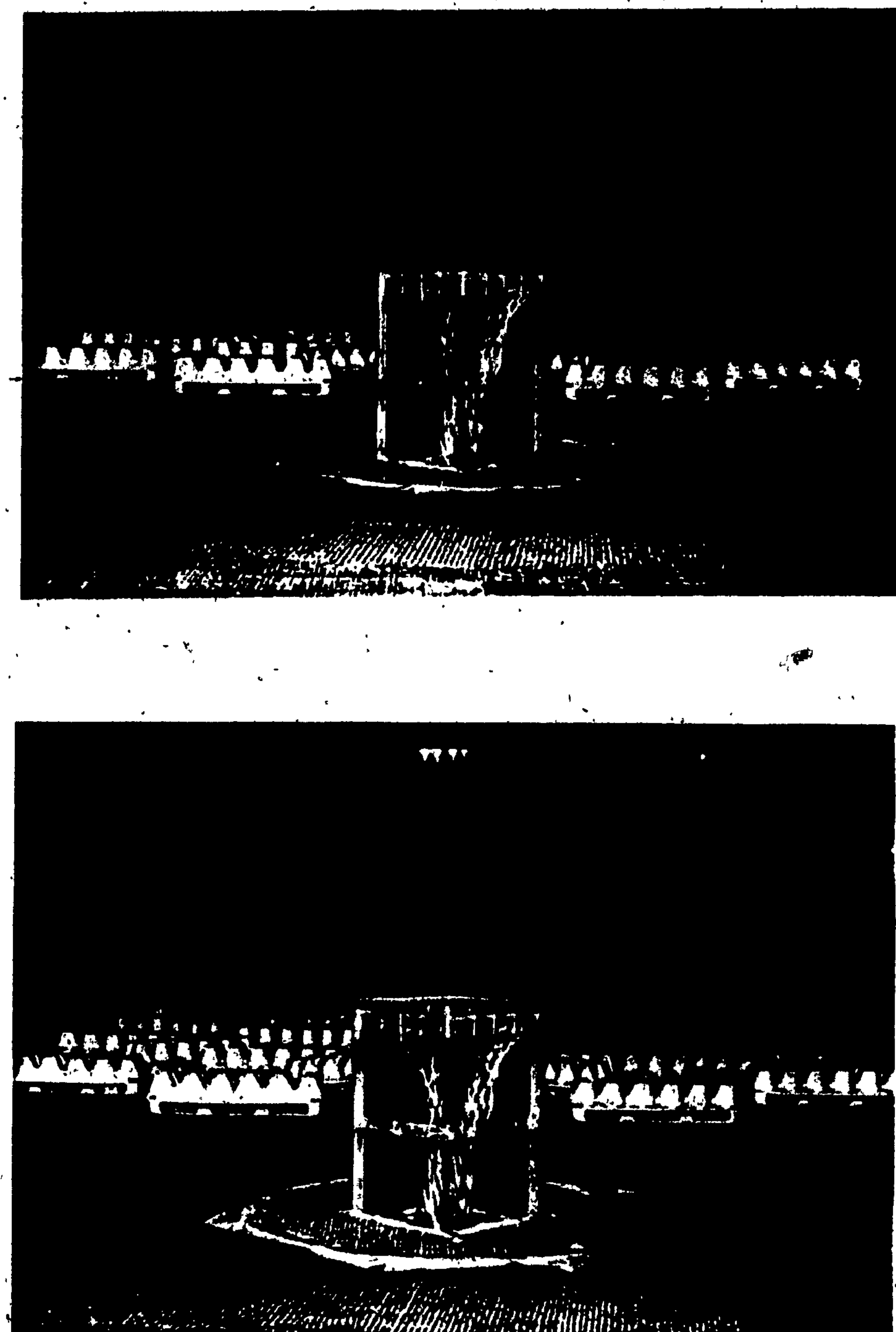


PLATE 3.3 BUILDING MODEL WITH AND WITHOUT PARAPETS IN URBAN TERRAIN

along with their model dimensions. As indicated in the previous chapter, this project is mainly dedicated to the effects of parapets on roofs of tall buildings. A low building 12m high has also been included in the experimental work, for comparison of the present study data with previous results.

The exact location of roof pressure taps is shown in Fig. 3.6. The pressure taps on one edge of the roof have been drilled as close as possible to the edge, in order to measure the critical wind effects expected on edges. Based on considerations of existing Standards and Building Codes of Practice (1,27) a number of different tributary areas have been selected on the roof for measurement of area-averaged loads. These areas are shown in Fig. 3.7.

Four parapet heights namely 0, 0.75, 1.5 and 3.0 m have been generally used. The high parapet of 3.0 m has been included in order to study the trends of the data to understand the extreme effect of parapets in detail. These parapets may also represent cases of buildings under construction or partly damaged. Additional parapets less than 0.75 m high (0.2, 0.3, 0.4, and 0.6 m) have also been tested for the detailed assessment of corner wind loads.

All buildings have been tested for several wind directions. The symmetry of the roof and the symmetric

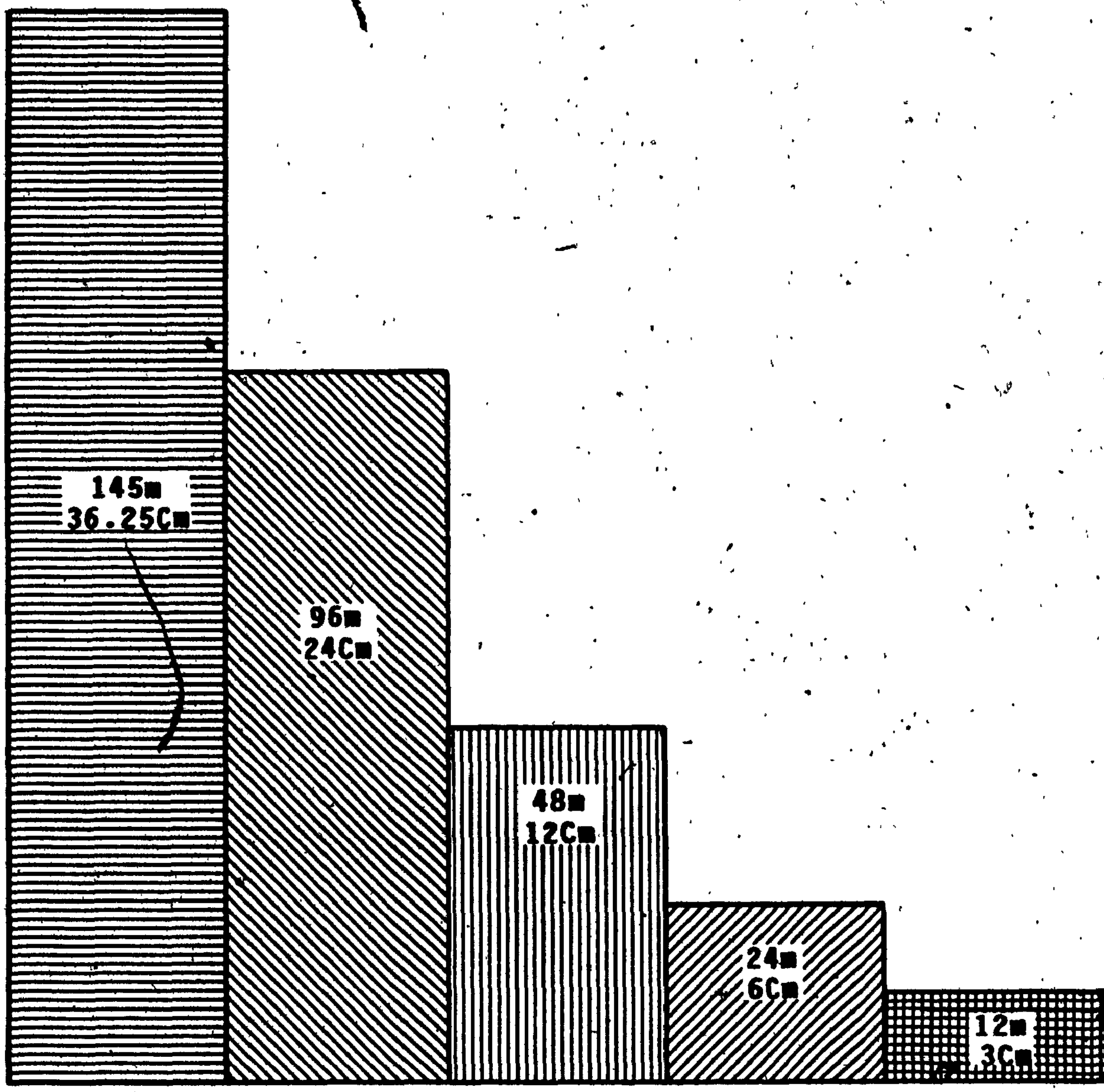


FIG. 3.5 TESTED BUILDING CONFIGURATIONS

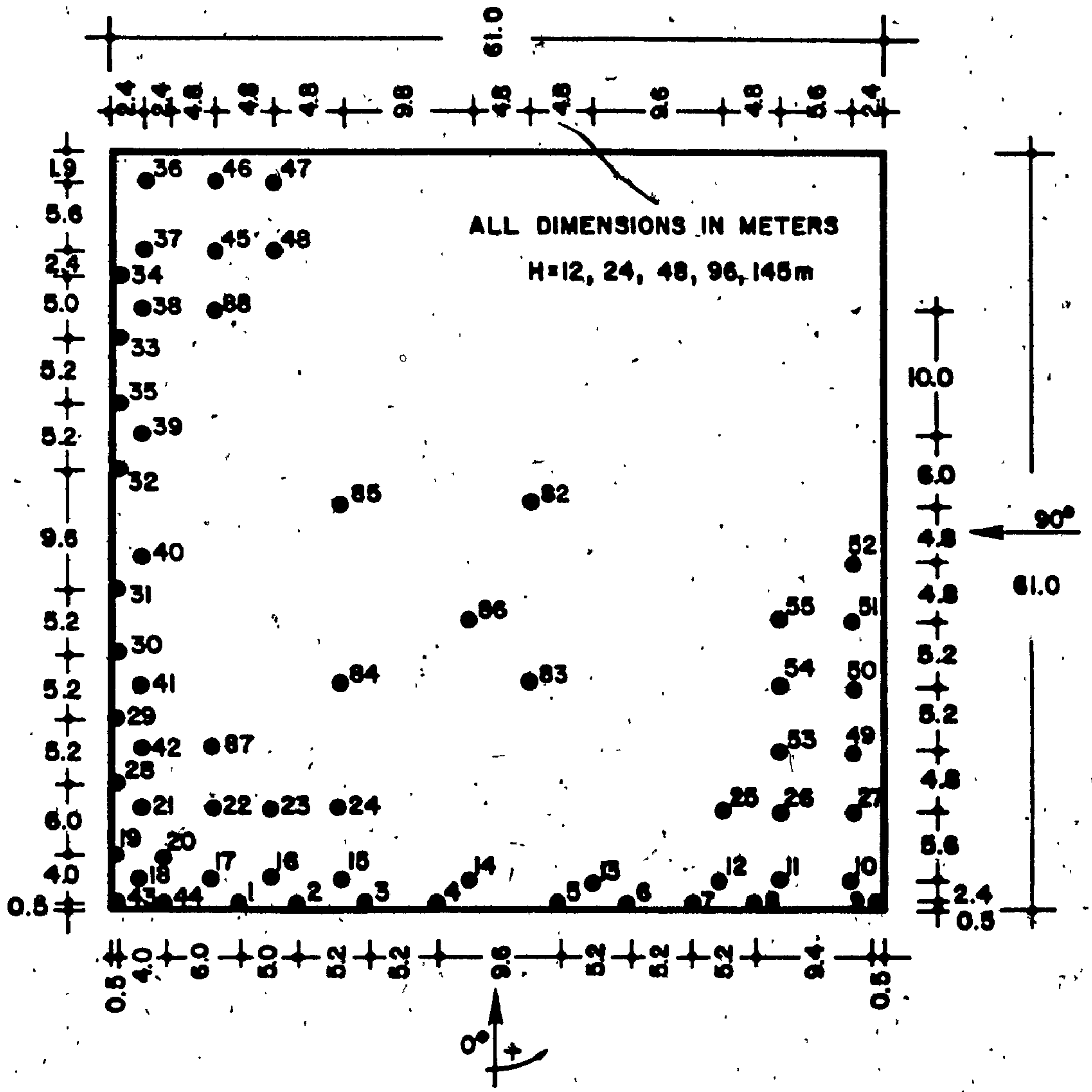


FIG. 3.6 FLAT ROOF MODEL AND PRESSURE TAP LOCATION

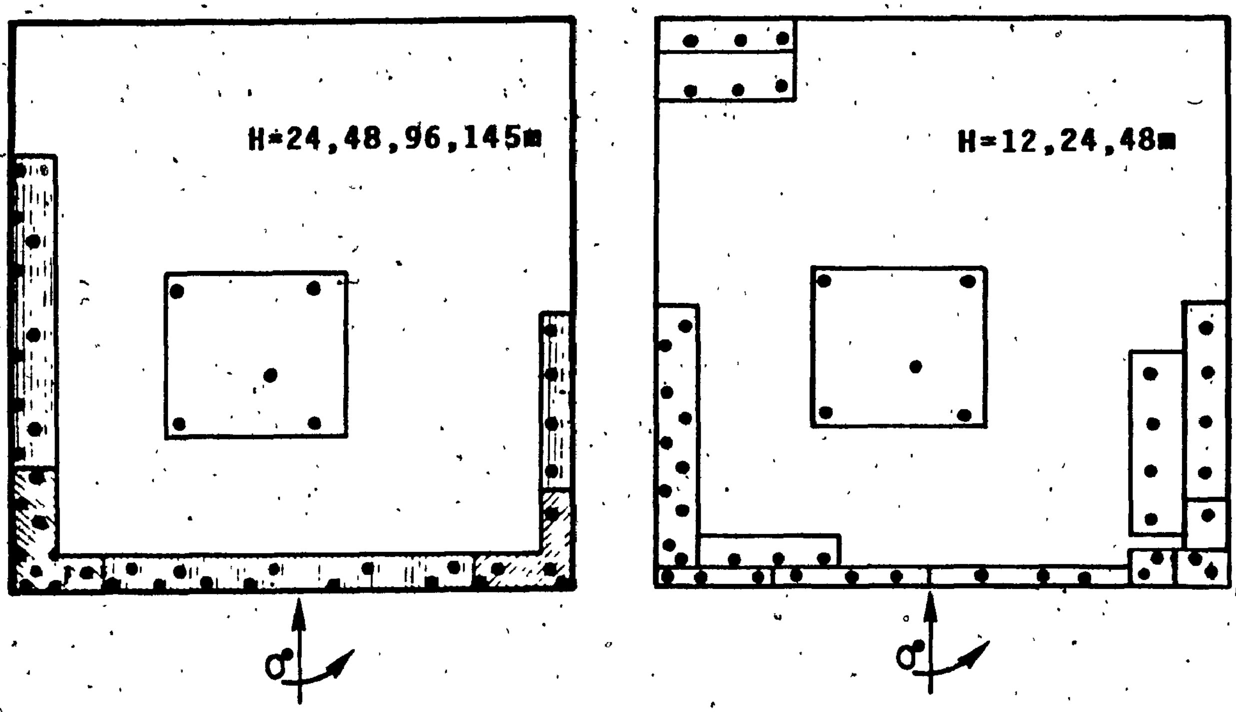


FIG. 3.7 AREAS CONSIDERED FOR MEASUREMENT OF AREA-AVERAGED PRESSURES

locations of pressure taps have also been considered when determining the necessary wind directions. A summarized, schematic diagram for the various configurations tested is presented in Fig 3.8

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 1.6 mm as shown in plate 3.4. The pressure measuring system in use at Centre for Building Studies, responds to pressure fluctuations on the model up 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.

Figure 3.9 shows diagrammatically the procedure followed for the local load and area-averaged pressure measurements. A sampling rate of 50 samples per second over a period of 30 seconds was used in the test. Sampling rate has more significant effect on the fluctuating peaks (43). Therefore for comparison purpose and for quality evaluation of peak pressure coefficients, experiments have also been carried out with a higher sampling rate (500

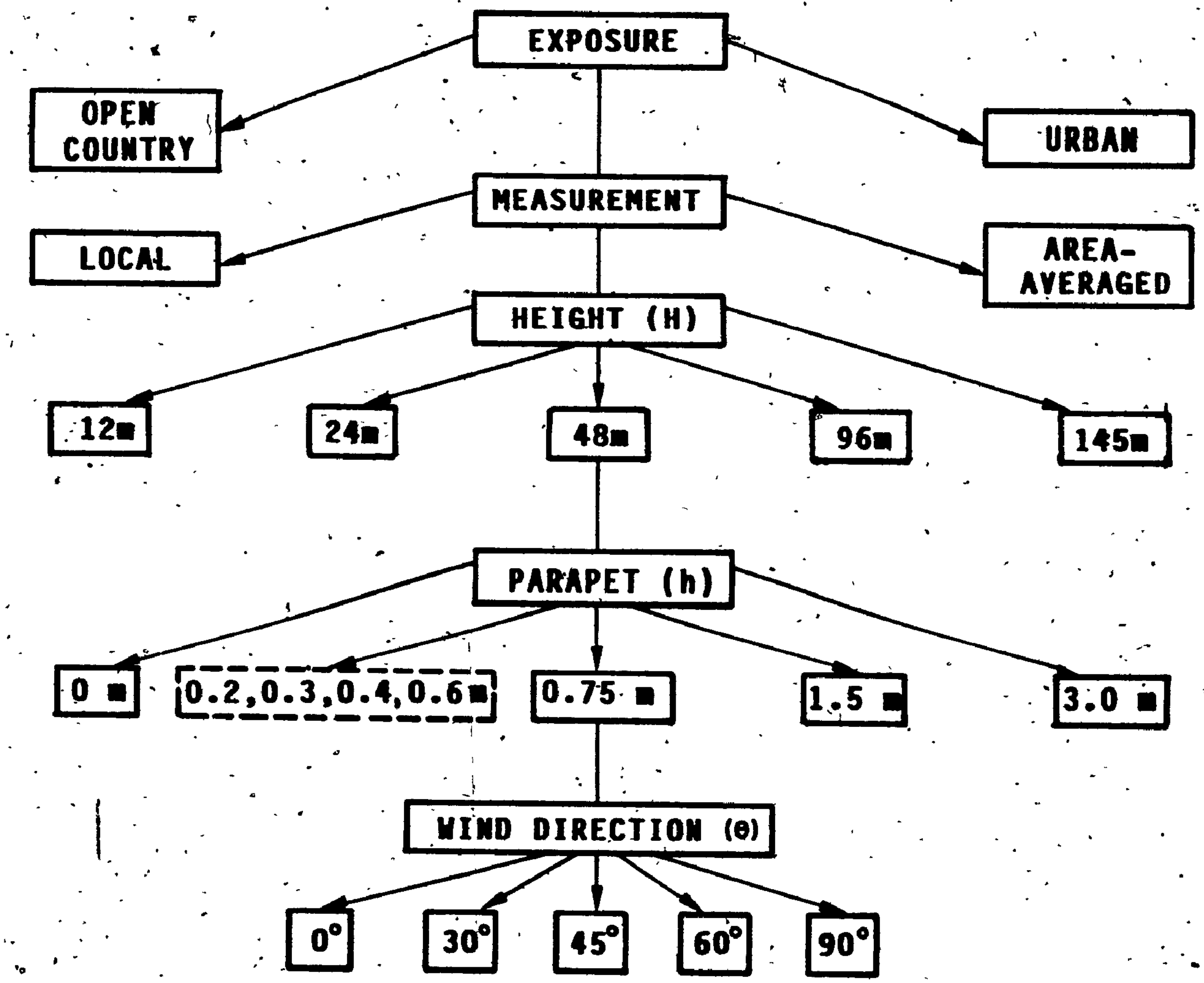
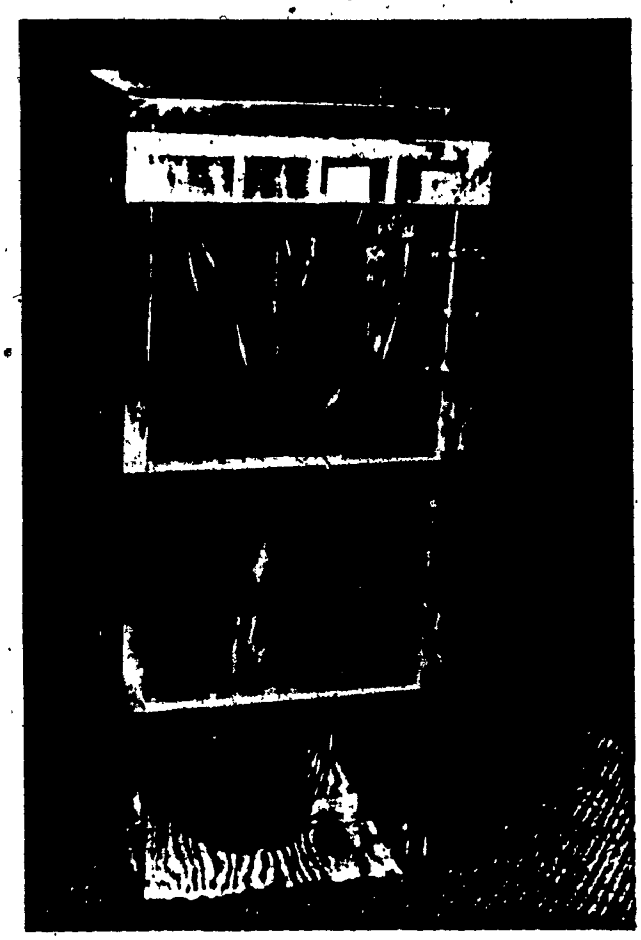


FIG. 3.8 VARIOUS CONFIGURATIONS TESTED



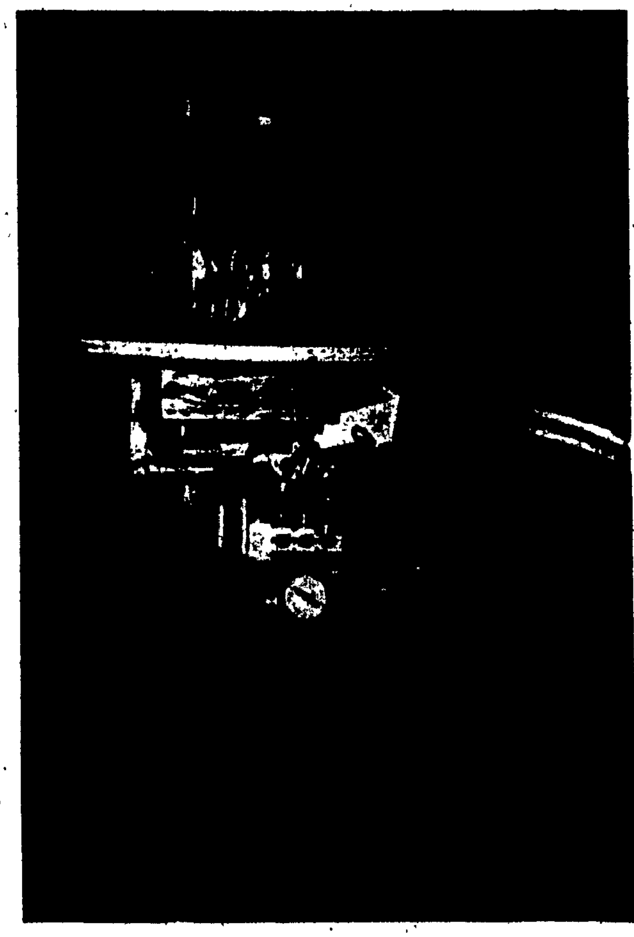


PLATE 3.4 TUBING CONNECTIONS FROM THE MODEL TO THE SCANIVALVE

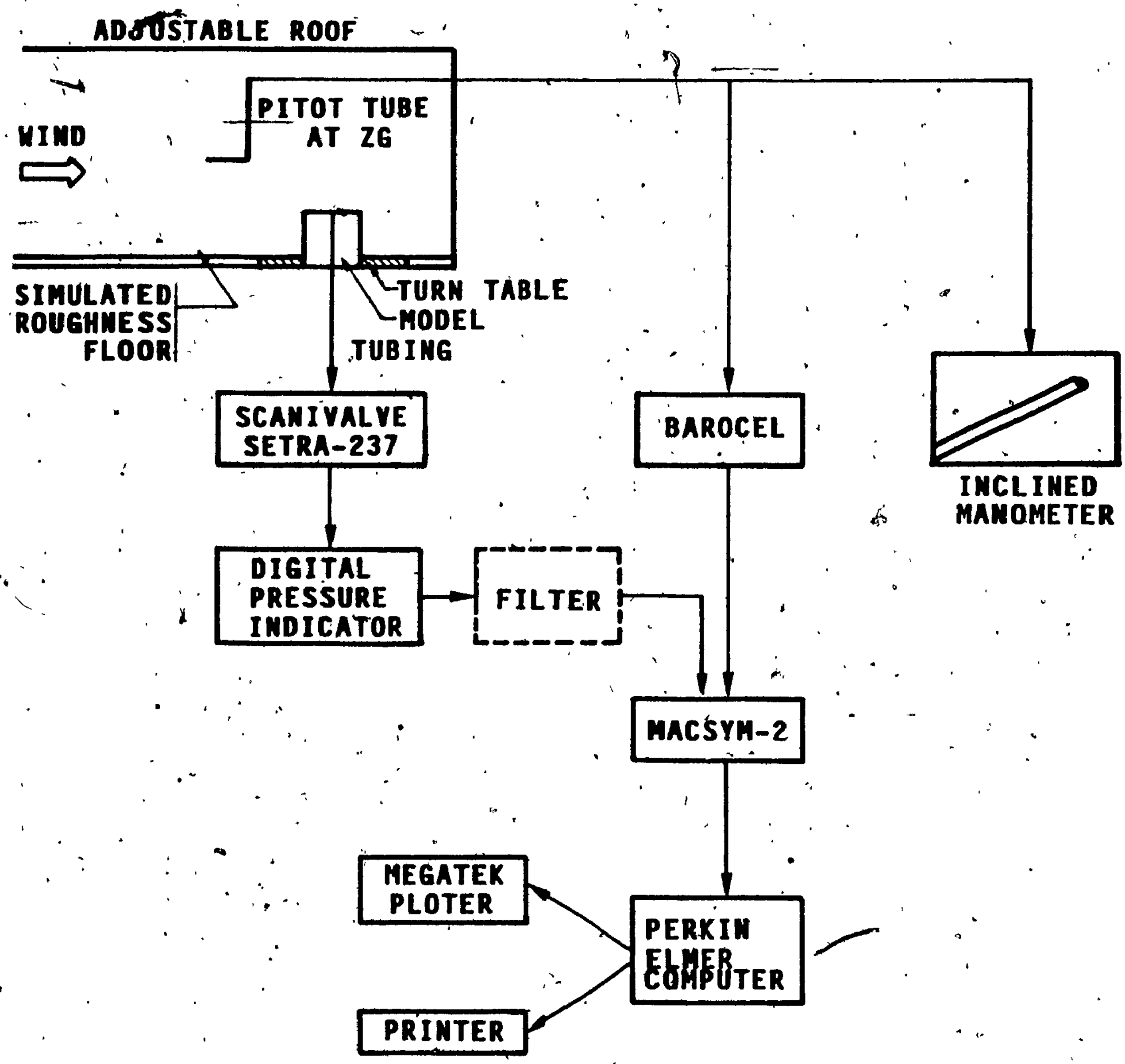


FIG. 3.9 EXPERIMENTAL SETUP FOR LOCAL AND AREA-AVERAGED PRESSURE MEASUREMENTS

samples per second) for a period of 15 seconds per second. 50 such records, have been collected for some points thus resulting in 375000 samples of data per point. Extreme value distribution analysis has been carried out for these points and the quality of the measured peak values has been established. Detailed discussion of this phenomenon will be presented in Chapter 5.

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 $\frac{1}{2}\rho\bar{V}^2$ 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 (Fig 3.2) such measured pressure coefficients can 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:

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

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

in which,

$\hat{P}$: the maximum instantaneous pressure measured over the smpling 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.

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

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

A pictorial representation of the all pressure coefficients is given in Fig 3.10. The mean pressure gives an indication of the static wind load that can be expected . The Cp, 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

TERRAIN	BUILDING HEIGHT H, (m)	HEIGHT FACTOR
OPEN COUNTRY	12	2.2
	24	1,7
	48	1.4
	96	1.2
	145	1.1
URBAN	12	3.9
	96	1.7

TABLE. 3.2 FACTORS RELATING DYNAMIC PRESSURE AT ROOF HEIGHT TO DYNAMIC PRESSURE AT GRADIENT HEIGHT

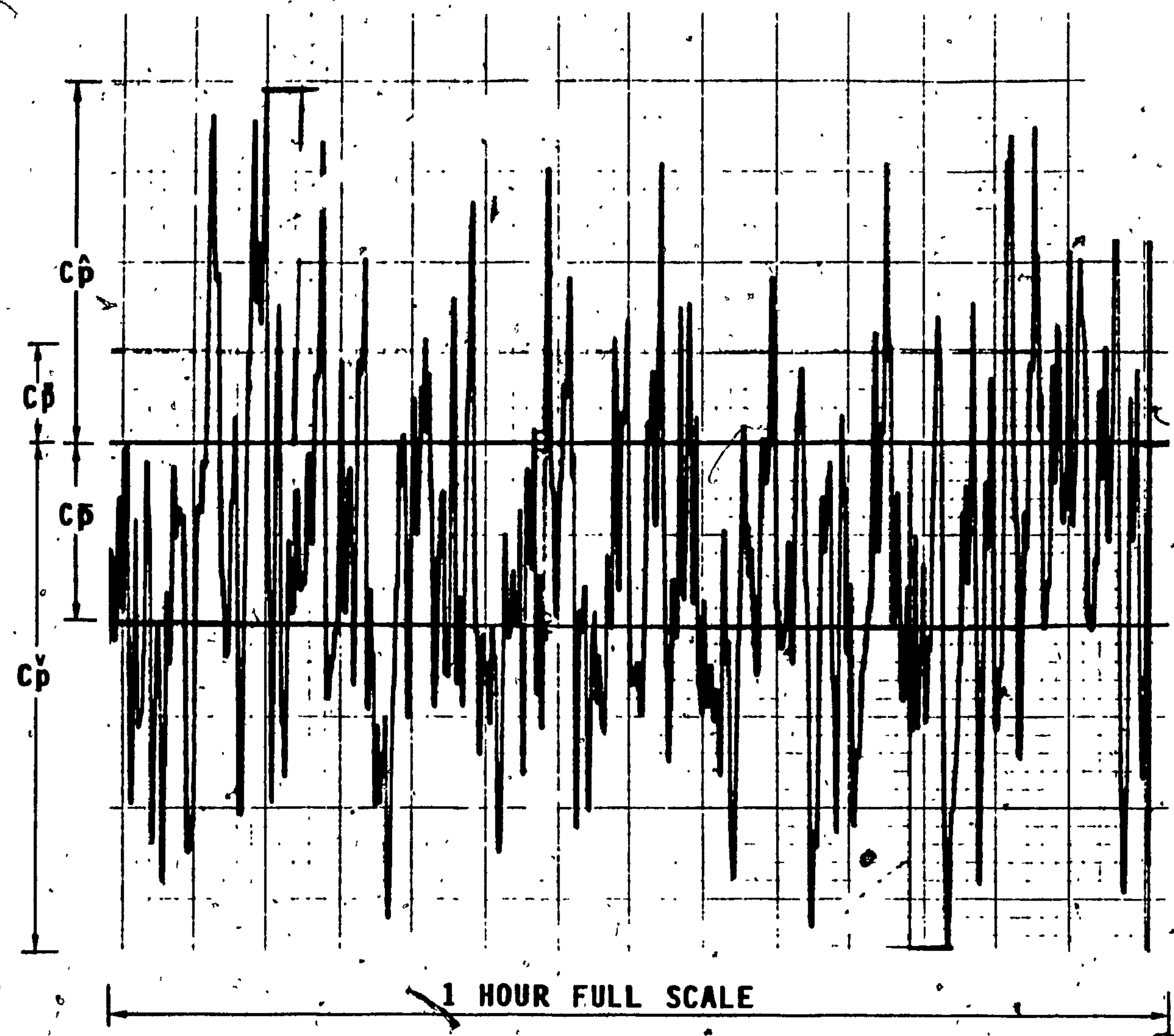


FIG. 3.10 DEFINITION OF STATISTICS OF PRESSURE COEFFICIENTS

coefficients have been recorded and their trends are analyzed and discussed in the next chapter.

CHAPTER 4

RESULTS AND DISCUSSION

" There has been some confusion in Wind Engineering about the actual effect of parapets on the wind loads acting on buildings. "

......T. Stathopoulos.

4.1 GENERAL

The experimental results are presented in this chapter. Some comparison of the present results with those of previous works are also made for validation purposes.

Most of Wind Standards and Building Codes of Practice divide the building roof into three regions, namely moderately loaded interior region; heavily loaded edge region; and maximum loaded corner region; and they provide differently loadings for each of these regions.

In order to better understand the effect of parapets on roof wind loadings the experimental results of this study are organized and presented in a similar fashion, but in four sections. The overall effect of parapet on roofs is discussed in the first section. The effect of parapet on the interior roof loadings are analyzed in the second section. The third section refers to the reduction/increase of wind loads on the roof edges due to parapet. Finally, the wind-induced roof corner loads are discussed and much attention is also paid in these corners where most of the roof failures occur in practice.

In all sections the effect of parapet on local loads acting on building roofs in open country and urban exposure is first discussed. Then the area-averaged wind loads measured in open country terrain are presented. In most cases both mean and peak pressure coefficient values are analyzed. For some configurations the rms pressure coefficient values are also compared for roofs with and without parapets.

4.2 CONFIRMATION OF THE PRESENT STUDY RESULTS

In Fig 4.1, the data of the present study are compared with the experimental results of Stathopoulos(38). The most critical Cp mean and Cp peak values from all different wind directions are considered for the windward edge of the roof. The top half of the figure presents data collected in

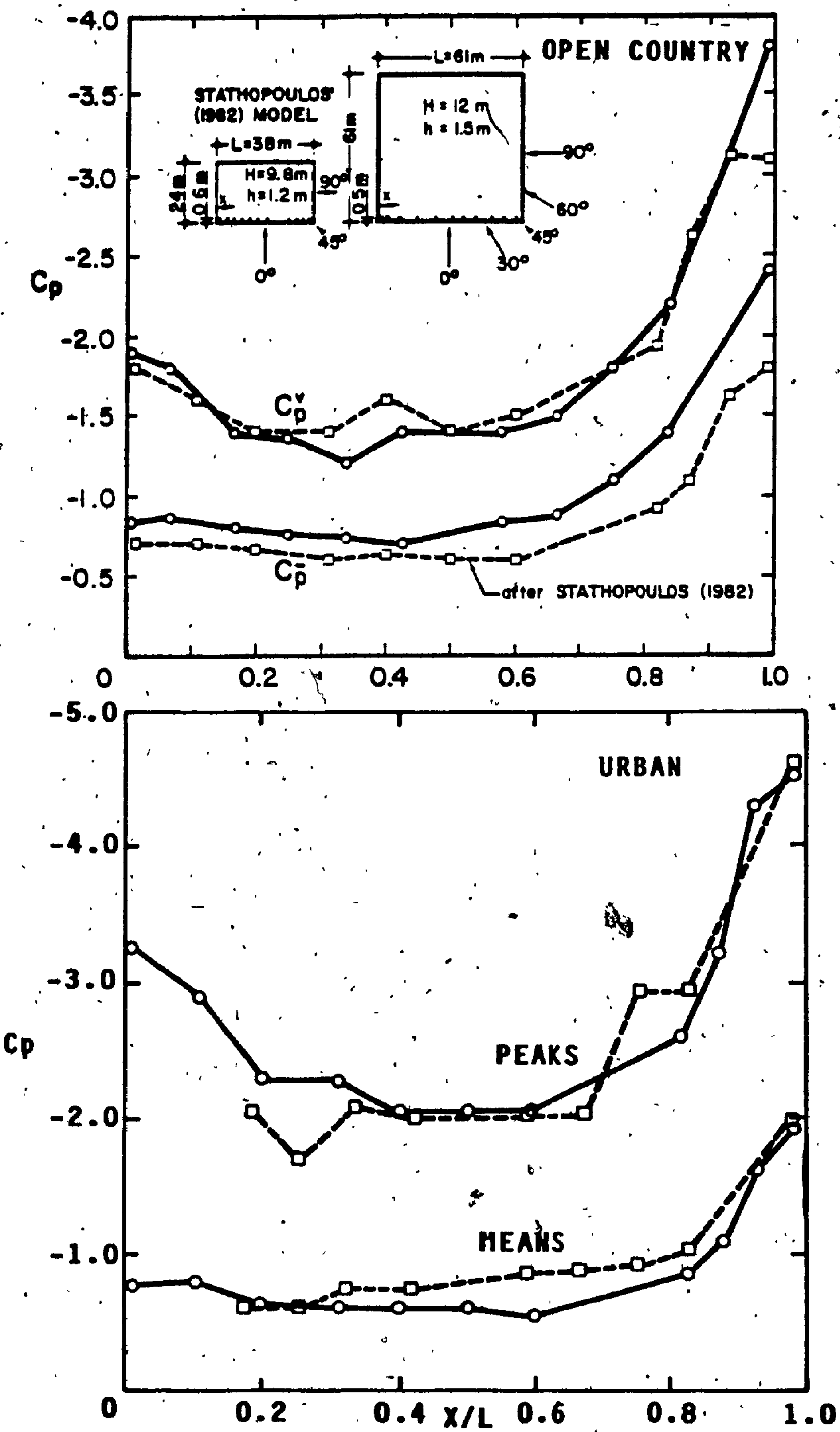


FIG. 4.1 COMPARISON OF PRESENT STUDY WITH STATHOPOULOS (38)

the open country exposure. Since previous data on the effect of parapets in urban terrain are not available it has been decided to compare the urban exposure(x = 0.37) data of the present study with the suburban exposure(x = 0.28) data of Stathopoulos(38). Typical results are shown in the bottom half of the figure. Generally, the agreement between the two studies is quite satisfactory. Some variations may be attributed to the difference in the model geometry and higher number of wind directions tested in the present study.

Figure 4.2 shows repeatability results of the experimental work. The two sets of mean pressure coefficient data compared have been measured 20 days apart. The agreement noticed is typical for other cases tested and it is quite encouraging. It also indicates the magnitute of errors or accuracy expected from these measurements. The small possibility of errors expected in the peak pressure coefficient values are discussed in Chapter 5 .

4.3 OVERALL EFFECT OF PARAPETS ON ROOF WIND LOADING

For each pressure tap on the roof both mean and peak pressure coefficients have been collected for five wind directions. The most critical among the five values was selected as the worst-azimuth case. Such critical pressure

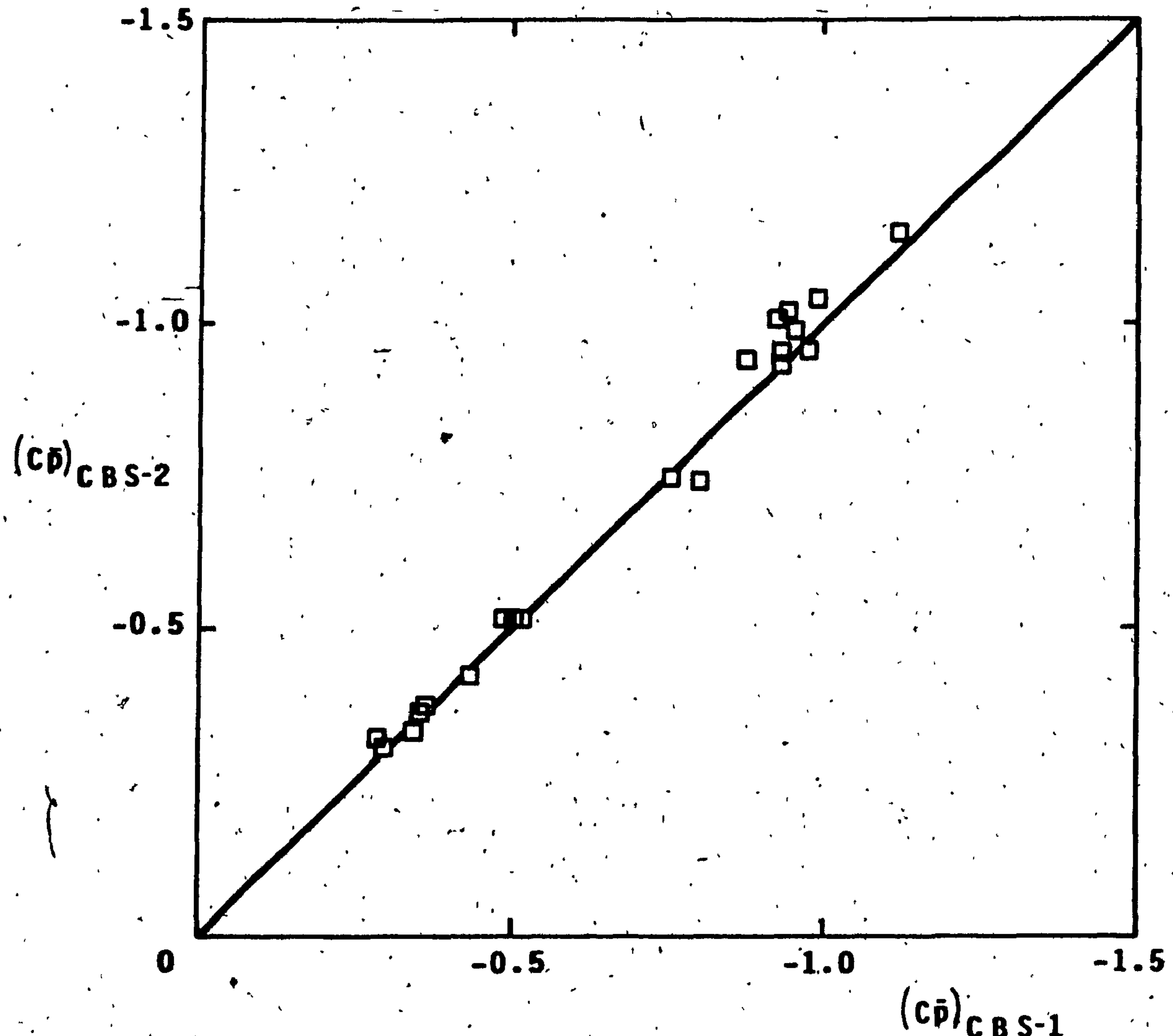


FIG.4.2 REPEATABILITY OF MEAN PRESSURE COEFFICIENTS

coefficients for all building heights tested are presented in Figures 4.3 and 4.4, for their mean and peak values respectively. Graphs have been arranged according to parapet heights and they refer to the open country exposure results. In general, data indicate that parapets 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 seem to benefit more for all parapet heights.

The corner taps form a distinct exception to this general conclusion. For low parapets the loads are increased on any building and for low buildings loads are increased by any parapet. Detailed discussion of the behaviour of corner taps is presented in the last section of this chapter.

To examine the effect of parapets on roof wind loading in urban terrain, a tall building (96m) and a low building (12m) have been tested for various wind directions. Results are presented for mean and peak pressure coefficients in Fig 4.5 in the same format as in figures 4.3 and 4.4 . Mean pressure coefficients are not much affected. However, it should be noticed that most of the peak pressure coefficient points lie below the reference line (45' line)- yielding high reduction in the design roof wind loads. The unique behavior of corner can also be noticed here.

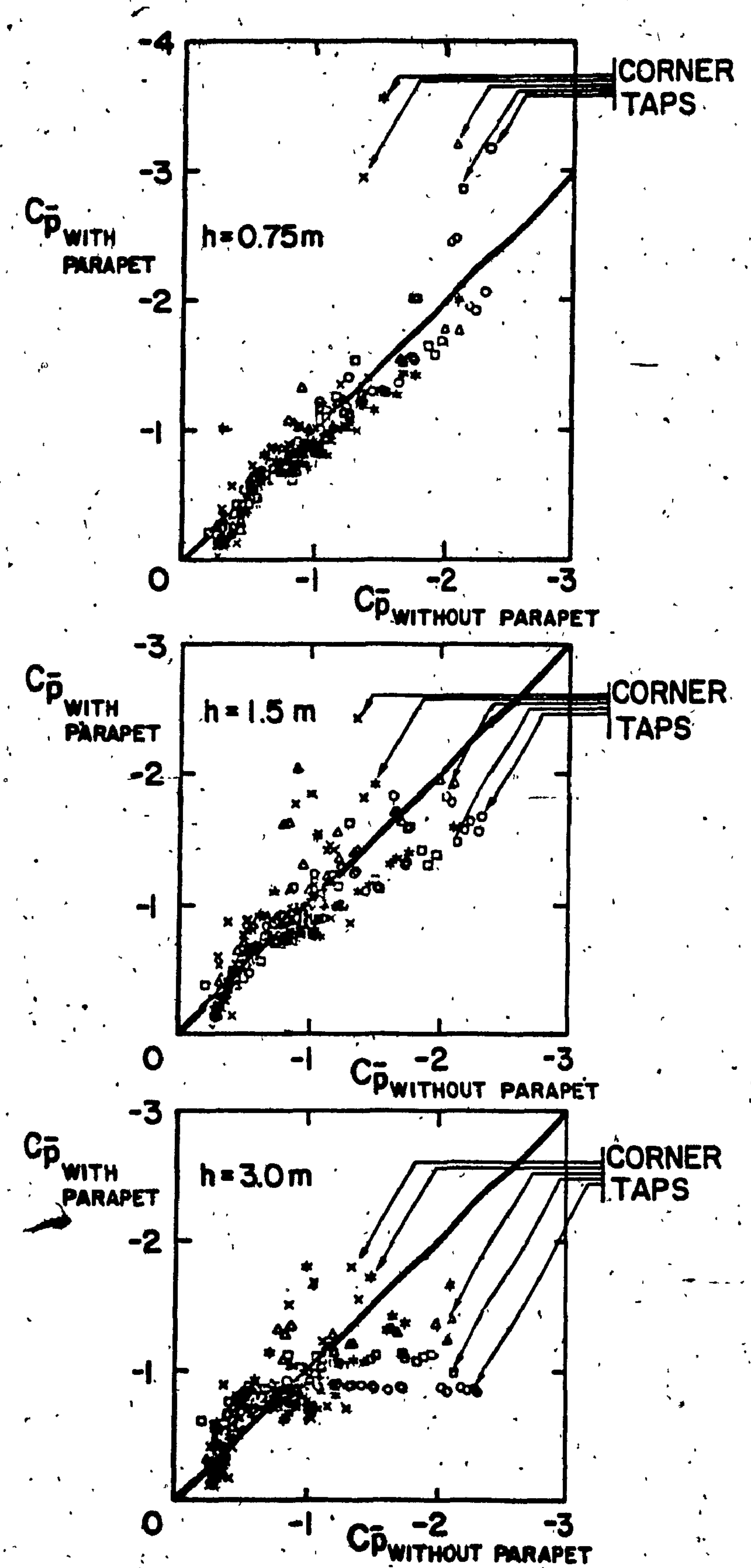


FIG. 4.3 EFFECT OF PARAPET ON MEAN PRESSURE COEFFICIENTS IN OPEN COUNTRY

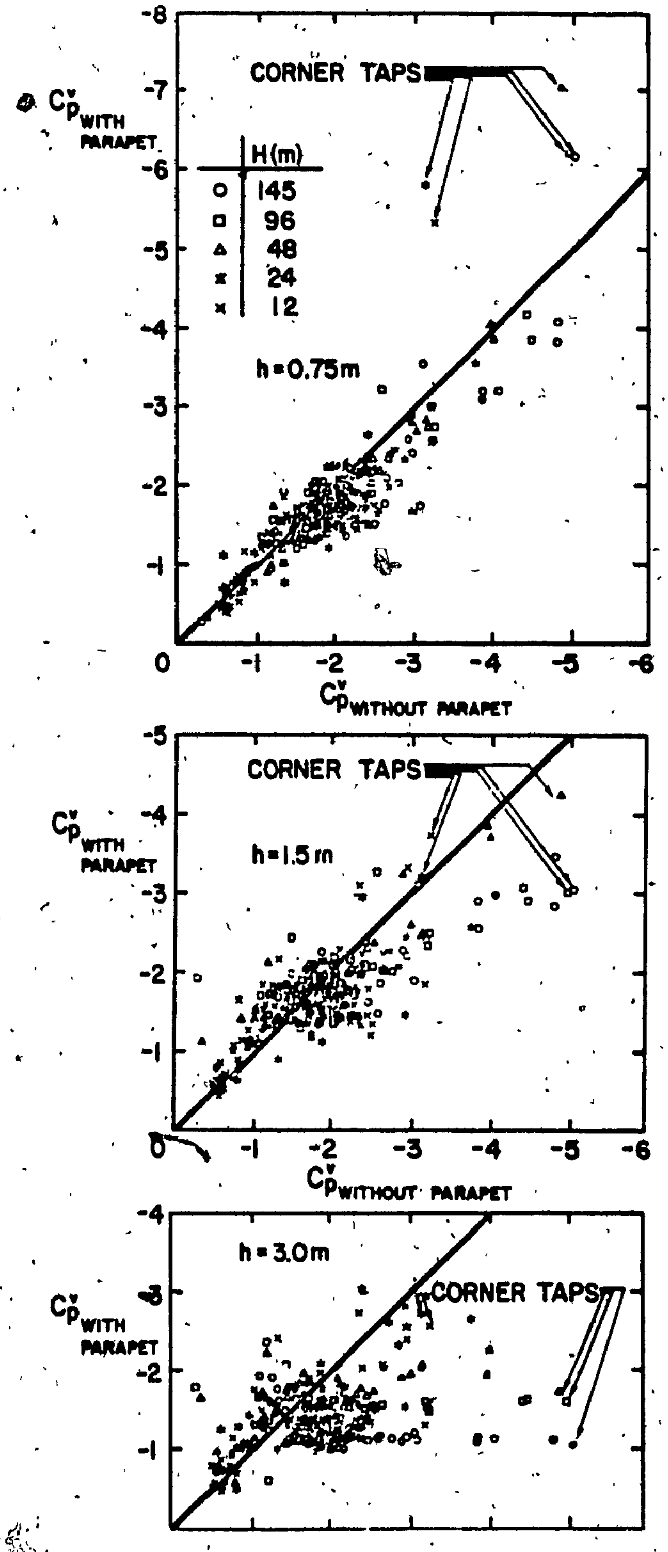


FIG. 4.4 EFFECT OF PARAPET ON PEAK PRESSURE COEFFICIENTS IN OPEN COUNTRY

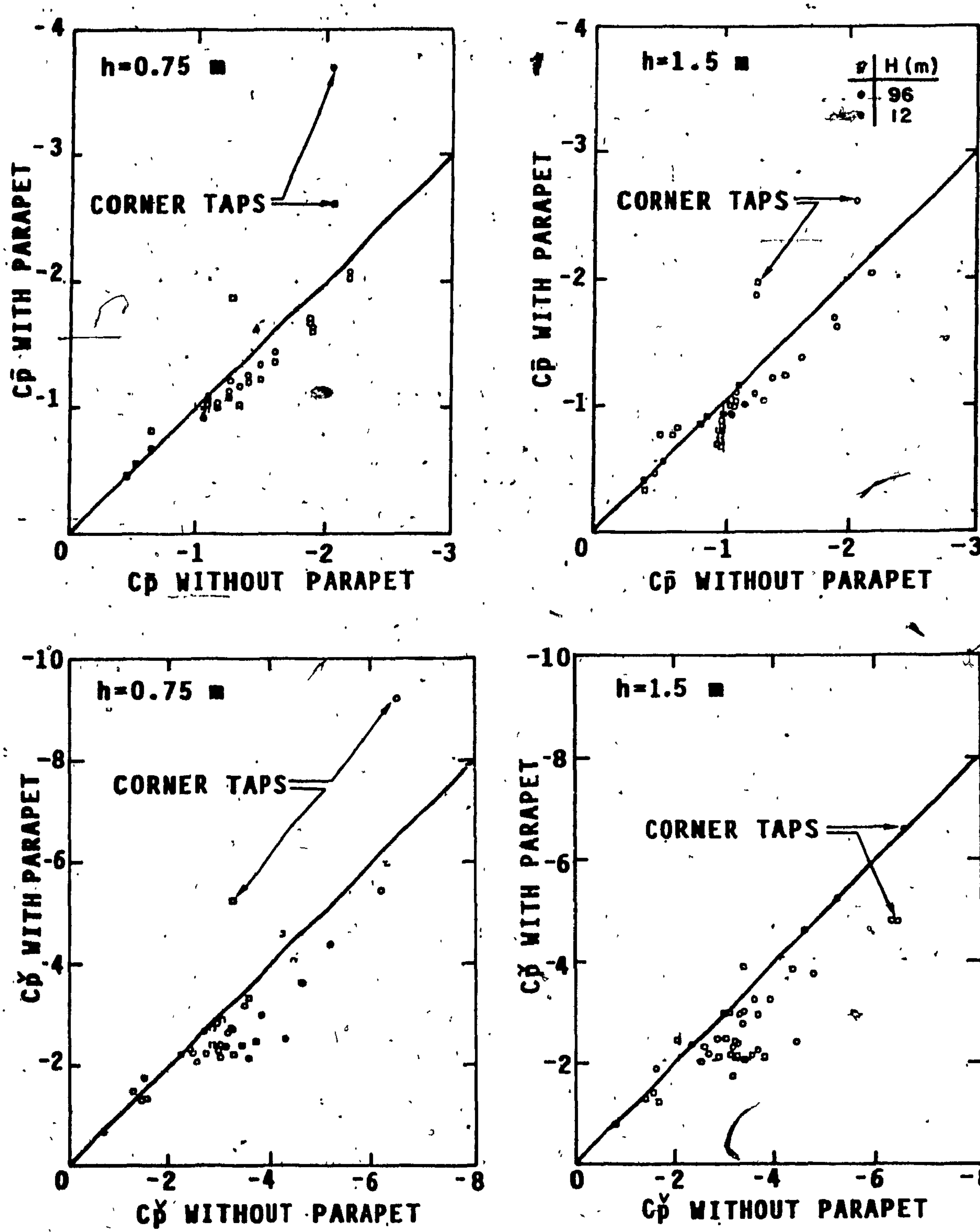


FIG. 4.5 EFFECT OF PARAPET ON MEAN AND PEAK PRESSURE COEFFICIENTS IN URBAN TERRAIN

To estimate the beneficial effect of parapets on different building heights, similar patterns of graphs are presented in Appendix 1 and Appendix 2, for the open country and urban terrain exposures. In global sense, the allevations remain the same. Nevertheless, the influence of the building height on the effect of a parapet shows a clear trend: the reductions are higher for taller buildings than lower buildings. By using data from the various configurations tested, the height effectiveness of a parapet, h/H, on the roof wind loading has been attempted but, unfortunately , no consistant trend has been found.

Area-averaged pressure measurements were also carried out during the experimental work as mentioned previously. Estimates of the area-averaged pressures were obtained for different tributry areas as shown in Fig.3.6 by pneumatically averaging the port pressures. Using this method (46) both peak and mean values of the area-averaged pressure coefficients have been collected and they are given in Fig 4.6 for a number of areas. Once again the figures confirm the general beneficial effect of parapets on the overall roof loadings with the exception of corner areas.

The physical mechanism behind the general reduction due to parapets on the roof is not very clear. However, this

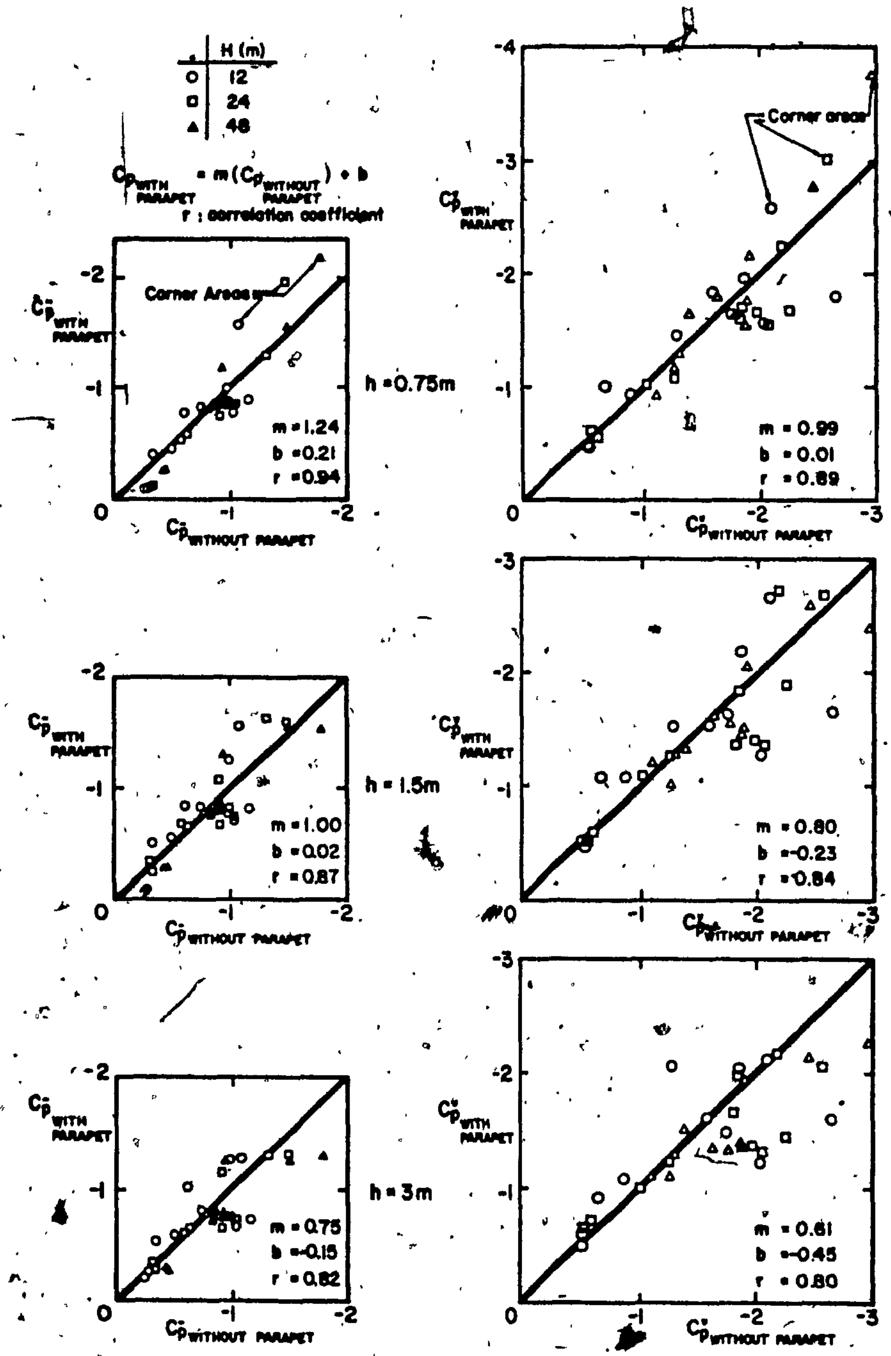


FIG. 4.6 EFFECT OF PARAPET ON AREA-AVERAGED PRESSURE COEFFICIENTS IN OPEN TERRAIN

reduction may be due to the fact that parapets tend to lift the shear layer or turbulence associated vortices away from the roof surface. This phenomenon will be further discussed at the end of this Chapter.

More detailed comparisons of the wind loads on building roofs with and without parapet have been undertaken by developing some kind of analytical model. Among the different attempts made, the pressure coefficient values have been fitted satisfactorily at least for some cases, by the linear regression model:

$$Cp \text{ with parapet} = m \, (Cp \text{ without parapet}) - b \qquad 4.1$$

where m and b are the parameters of the model and they represent the slope and intercept of the regression line respectively.

Note that when m approaches unity and b approaches zero, the regression line shows no statistical difference for the two sets of data ie., roof pressure coefficients with and without parapet. The parameters of linear regression model are presented in Fig 4.7. The linear regression equation is meaningful if the correlation coefficient "r" for the two sets of data is high enough- say more than 0.75. For the 3.0 m high parapets this is not satisfied. The correlation coefficients are generally higher for the mean values in comparison to the peaks. This shows that the peaks are more

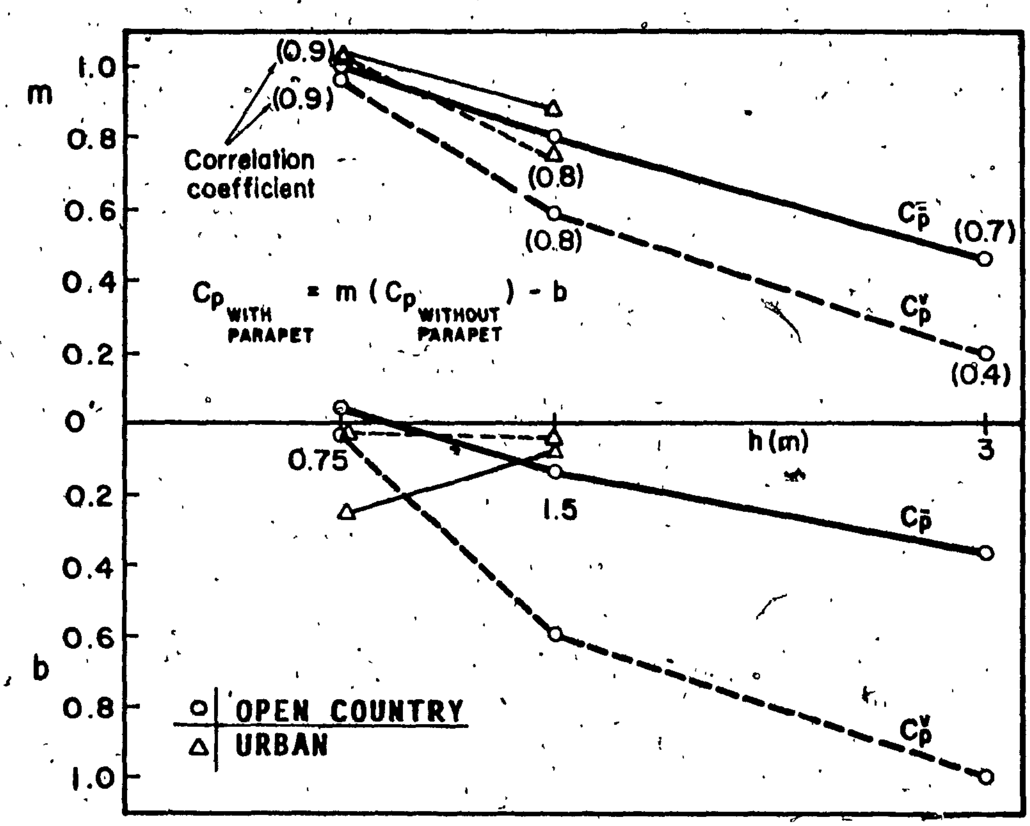


FIG. 4.7 LEAST SQUARE FITTING PARAMETERS FOR MEAN AND PEAK PRESSURE COEFFICIENTS

scattered. Similarly the m and b values for the individual building height studied are shown in Fig. 4.8, the values of which correspond to the graphs in Appendices 1 and 2.

Using Equation 4.1 together with the value of m and b, one is able to estimate approximate wind pressure coefficients for the entire roof of a building with parapets. Interpolation of the values may also give the general trend for other parapet heights not included in the experimental work. Since this model has been formulated based on the general experimental data its application for pressure evaluations at specific points of the roof is not advisable.

4.4 EFFECT OF PARAPETS ON WIND-INDUCED LOADS ON ROOF INTERIOR REGIONS

Five pressure taps on the interior area of the roof have been selected, as shown in Fig 3.6 and local and area-averaged wind pressures have been collected for all configurations tested. Results are discussed in this section.

Figure 4.9 shows the most critical mean and peak pressure coefficients of five taps for a tall building with and without parapets both in open country and urban terrain

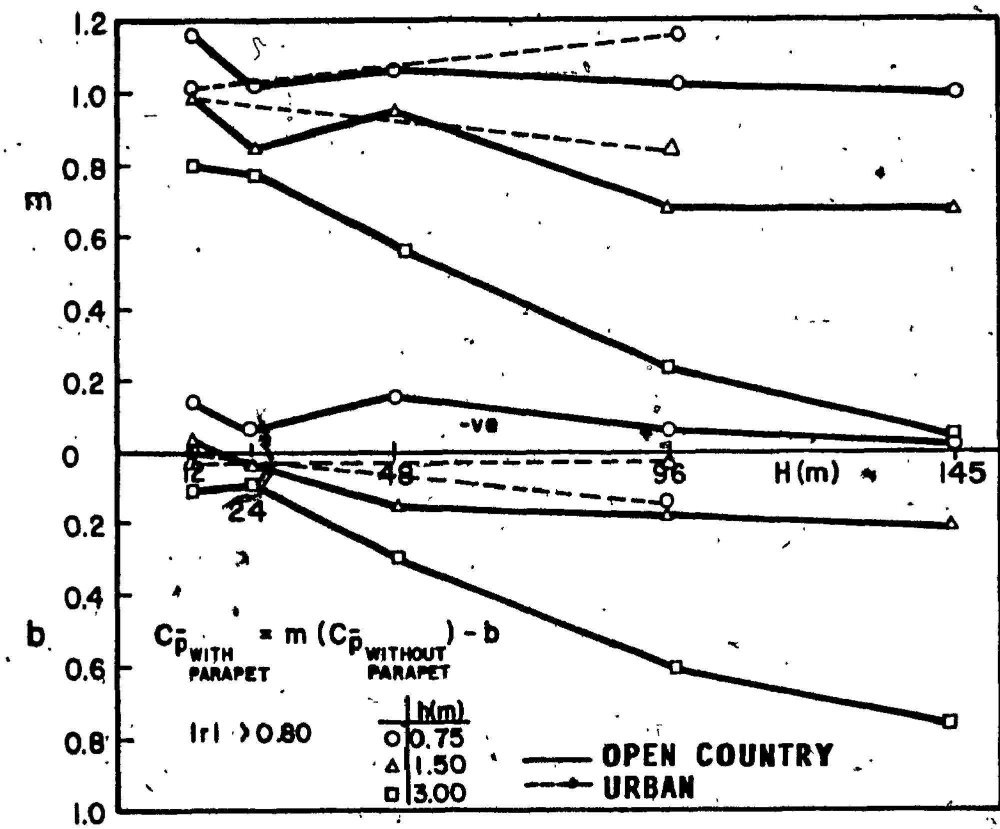


FIG. 4.8 LEAST SQUARE FITTING PARAMETERS FOR MEAN AND PEAK PRESSURE COEFFICIENTS FOR VARIOUS PARAPETS

exposure. Here Cp's are plotted against the angle of attack to examine the directional effect of the wind. Data indicate that, in general, mean pressure coefficients are affected neither by the direction of the wind nor by the parapet heights in any exposure. There seems to be more variation of the peak values with the direction of the wind particulary in the urban exposure. This may be caused by the increased turbulence of the urban exposure .

The little effect of parapets on the interior regions of the roof is apparent in Fig 4.10. The most critical Cp values measured for all building heights tested are presented. Typically on all buildings the interior loads remain constant for all heights of parapet tested. Even the terrain effect is found to be little.

Figure 4.11 shows the area - averaged wind loads measured on two buildings in open country terrain. The influence of wind directions on any parapet is small for the cases tested. Area-averaged pressure coefficients of the roof internal area of various buildings tested are given in Fig. 4.12. These pressure coefficients remain constant for buildings higher than 50 m whereas they decrease by decreasing the building height.

Although the windward parapets lift the air flow over the roof, leeward parapets have the opposite effect and deflect

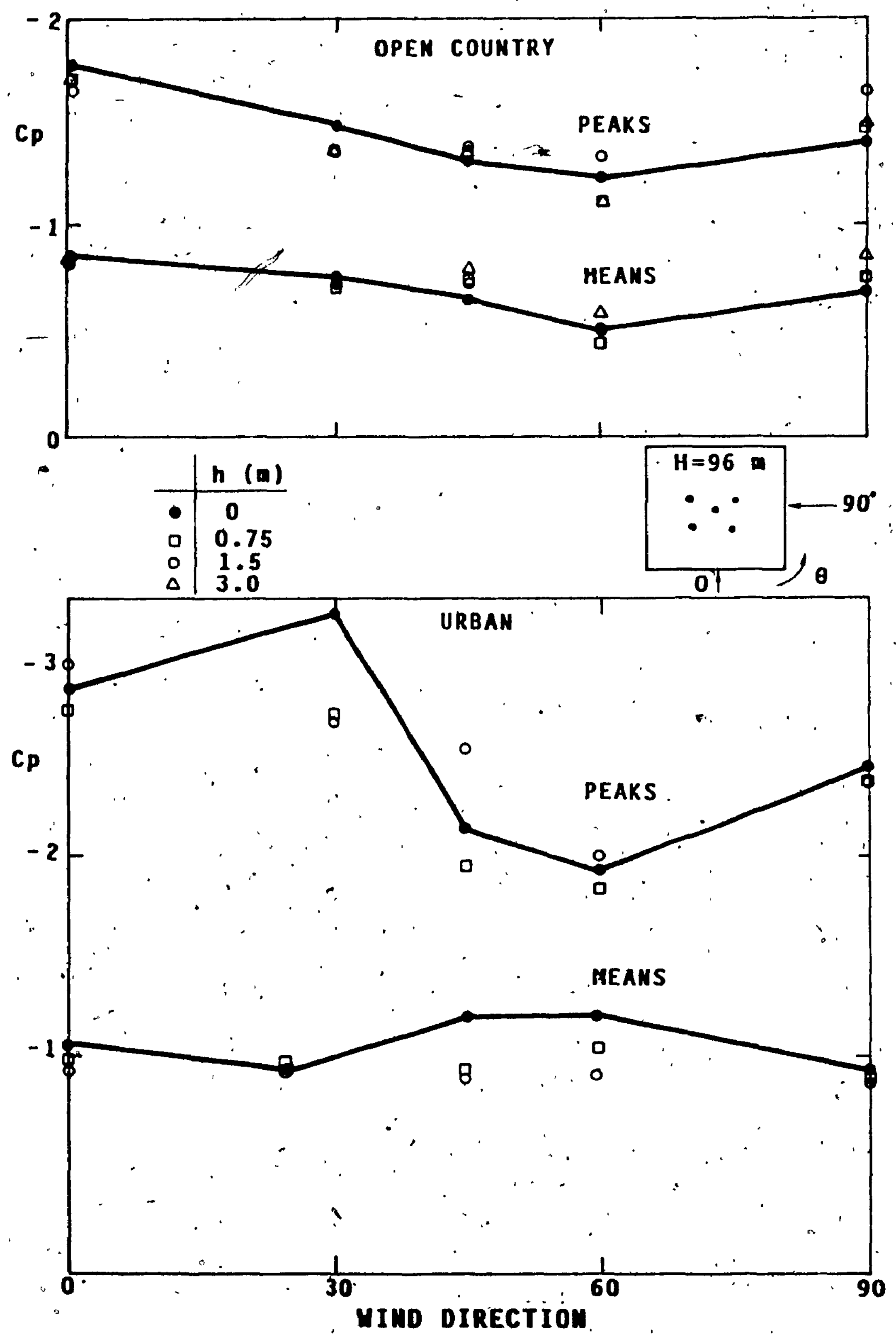


FIG.4.9 PRESSURE COEFFICIENTS ON INTERIOR POINTS OF FLATROOFS WITH AND WITHOUT PARAPETS

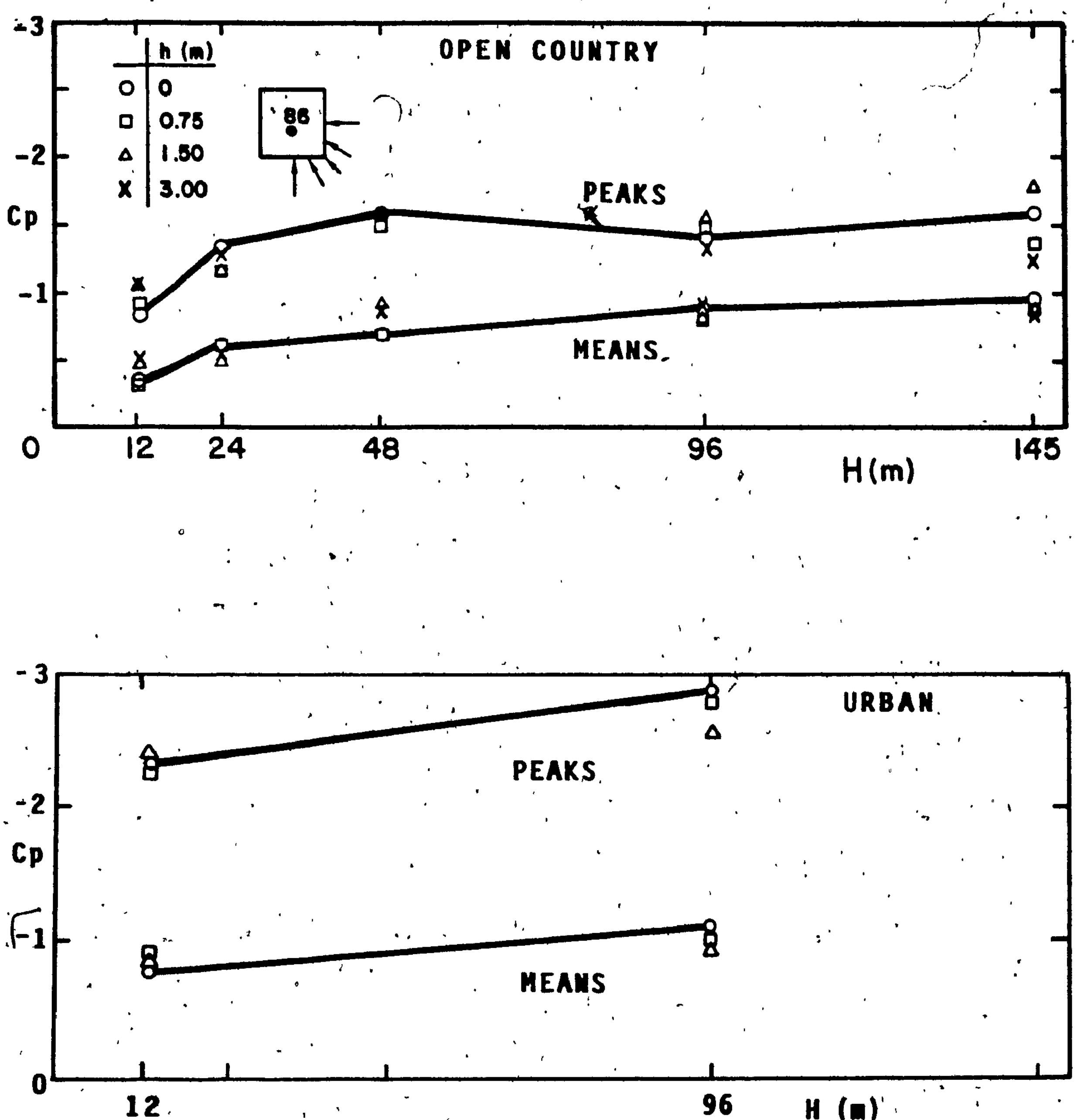


FIG. 4.10 MOST CRITICAL PRESSURE COEFFICIENTS FOR AN INTERIOR POINT OF FLAT ROOF WITH AND WITHOUT PARAPETS

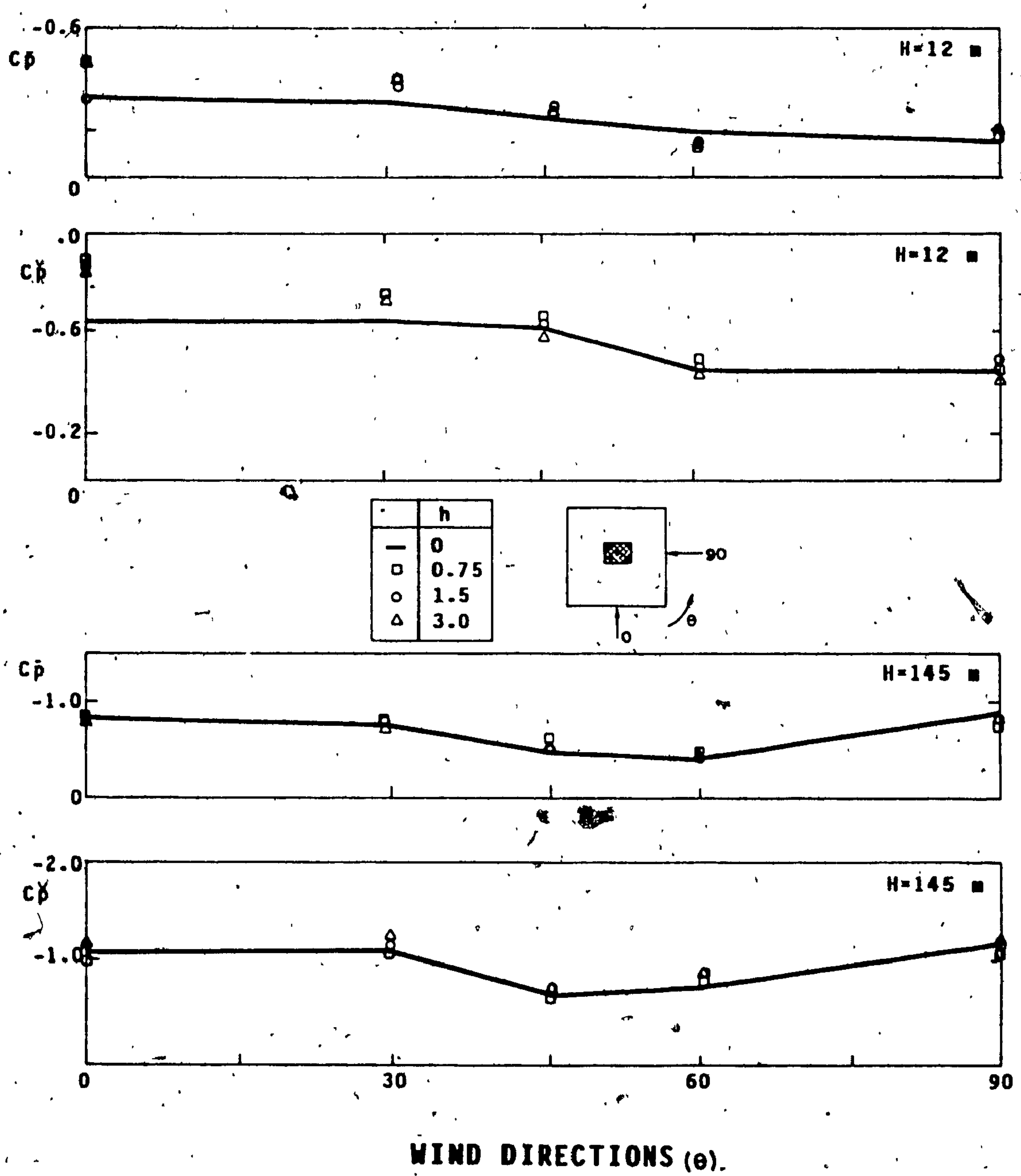


FIG.4.11 AREA-AVERAGED PRESSURE COEFFICIENTS FOR ANY INTERIOR ROOF AREA (OPEN COUNTRY)

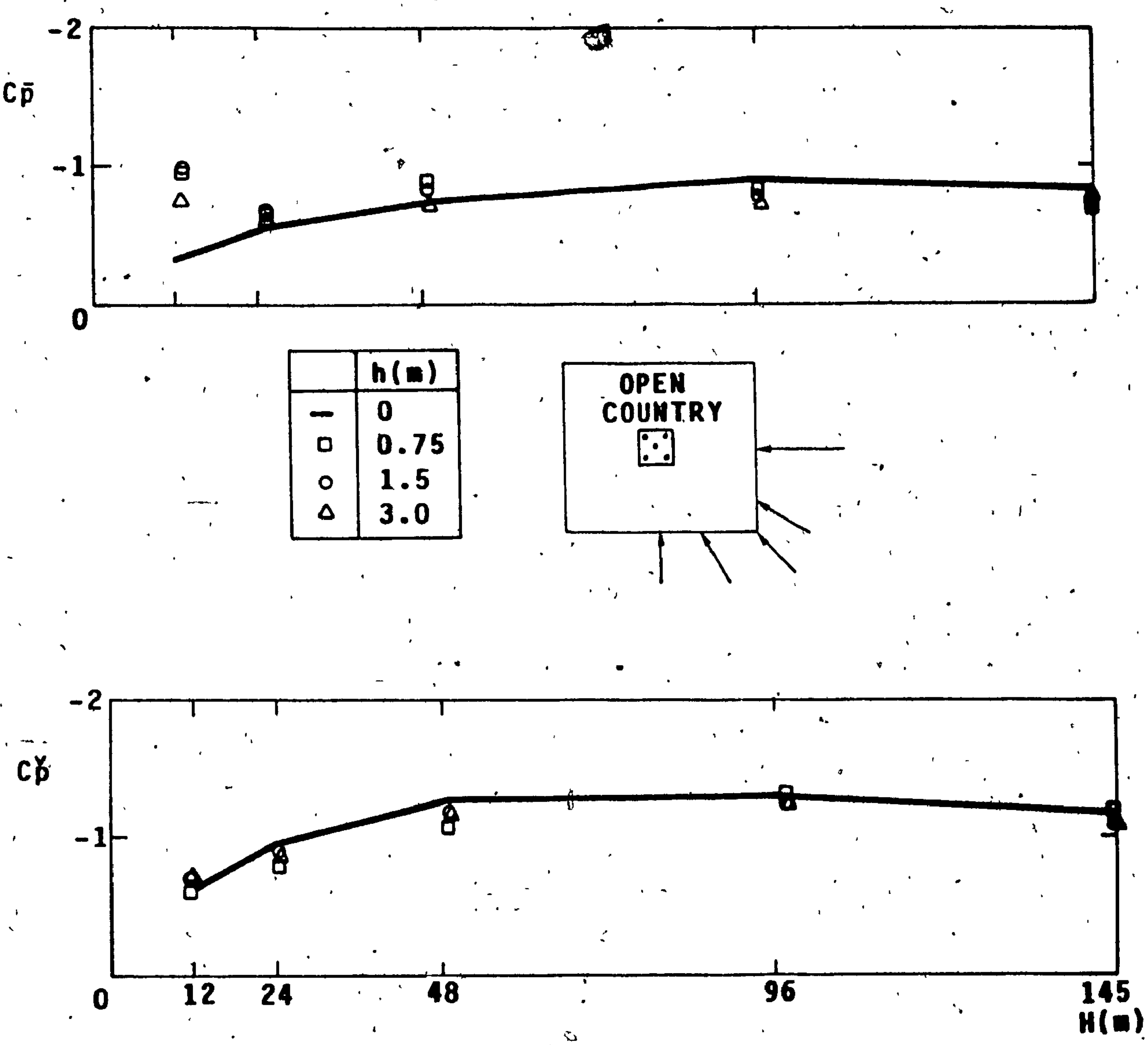


FIG. 4.12 THE EFFECT OF PARAPETS ON AN INTERIOR ROOF AREA FOR BUILDINGS OF VARIOUS HEIGHTS

the air flow back down onto the roof. Thus the total effect of the parapets on the interior roof areas appears to be insignificant. This found true for all building heights and wind directions in both exposures examined.

Further study would be recommended to understand the effect of parapet on roof interior areas. This can be analyzed by fixing parapets only around some sides of the building roofs instead of using a perimetric parapet as was the case of the present study.

4.5 WIND LOADS ON ROOF EDGES WITH PARAPETS

Wind loading is more sensitive closer to the edge from which the flow separates. Information about wind loads on roof edges is available in the literature. However, the changes in the loading of roof edges due to parapets are very seldom to find. As discussed in the previous chapter, some pressure taps have been drilled very close (0.125cm on the model) to the roof edge in order to measure the parapet effect as accurately as possible. This section will present and discuss the changes in wind loading on roof edges caused by parapets.

Figures 4.13 and 4.14 present mean and peak pressure coefficients respectively on the roof edges with and without parapets. Results are given for the tallest building tested in each terrain condition for normal wind direction. Even though the vertical scale in these figures is exaggerated, the predominant effect of parapets in reducing the curvature of the shear layer and consequently decreasing the wind pressures is clear to understand . The cases presented are for a 0.75m high parapet. Lower parapets have also been tested for some edge taps of a tall building. Results are given in Fig 4.15 for both mean and peak pressure coefficients measured at three different edge taps. Cp values are reduced with the increase in parapet height, in particular peaks show steeper reduction than means.

To elaborate on these changes of roof edge loading due to the parapets data have been expressed in terms of Precentage of Variation (P.V) . This is related to pressure coefficients and may be calculated by using the following expression:

P.V = Cp without parapet - Cp with parapet /Cp without parapet.

where Cp will be either the peak or mean pressure coefficient. Positive P.V's indicate reductions in the suction roof loads caused by parapets whereas negative

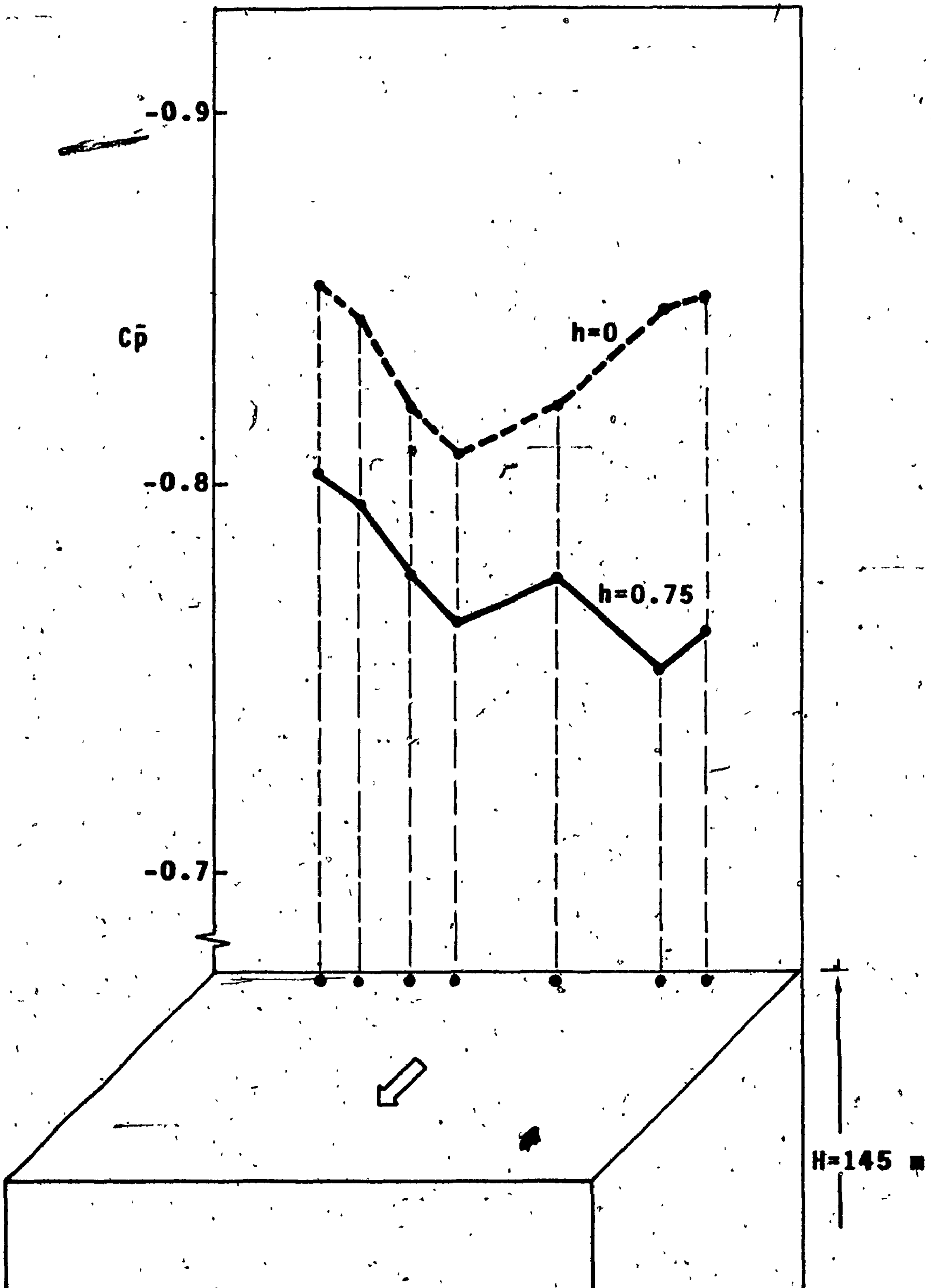


FIG. 4.13 a. PARAPET EFFECT ON MEAN PRESSURE COEFFICIENTS FOR FLAT ROOF EDGES (OPEN COUNTRY)

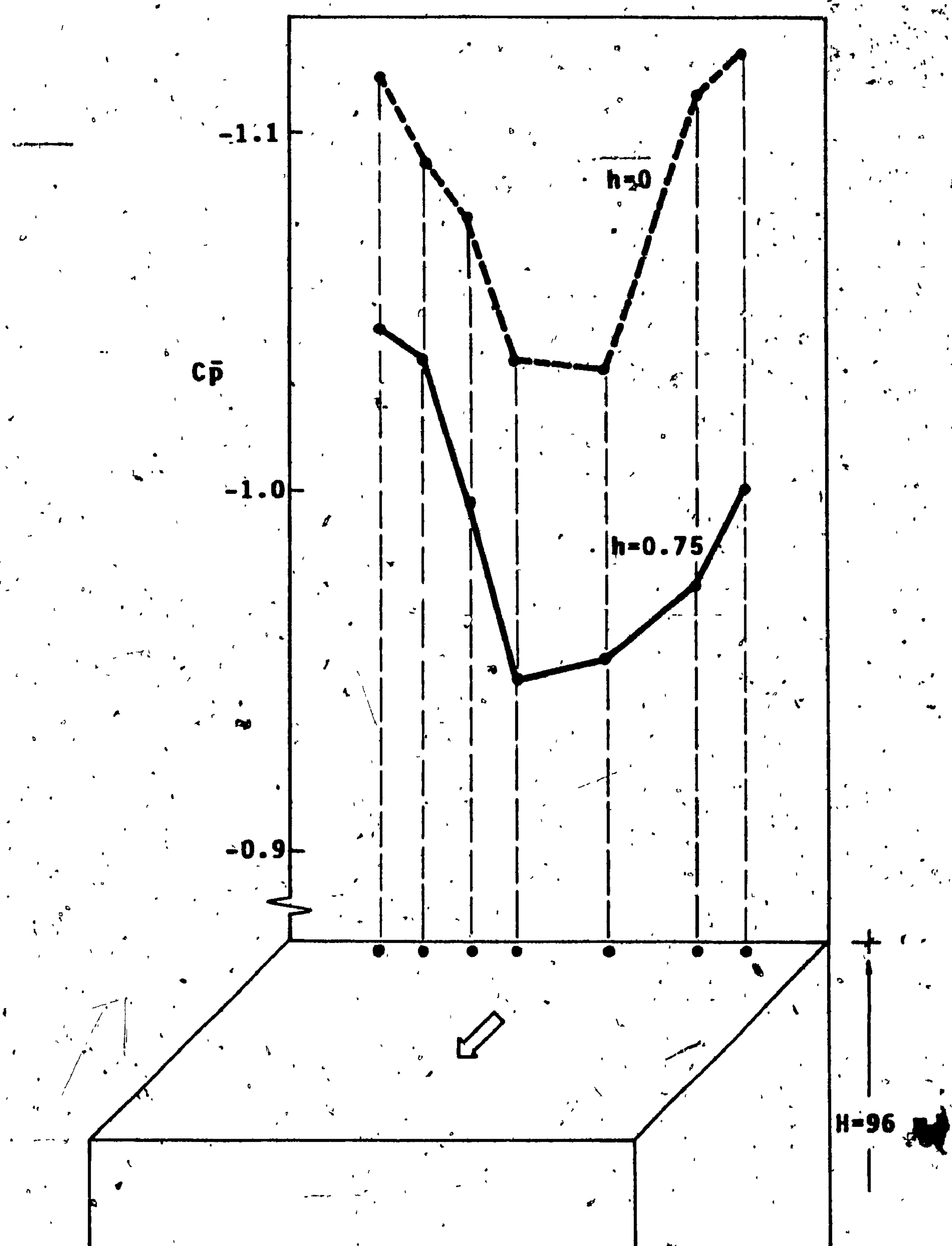


FIG. 4.13b. PARAPET EFFECT ON MEAN PRESSURE COEFFICIENTS FOR FLAT ROOF EDGES (URBAN)

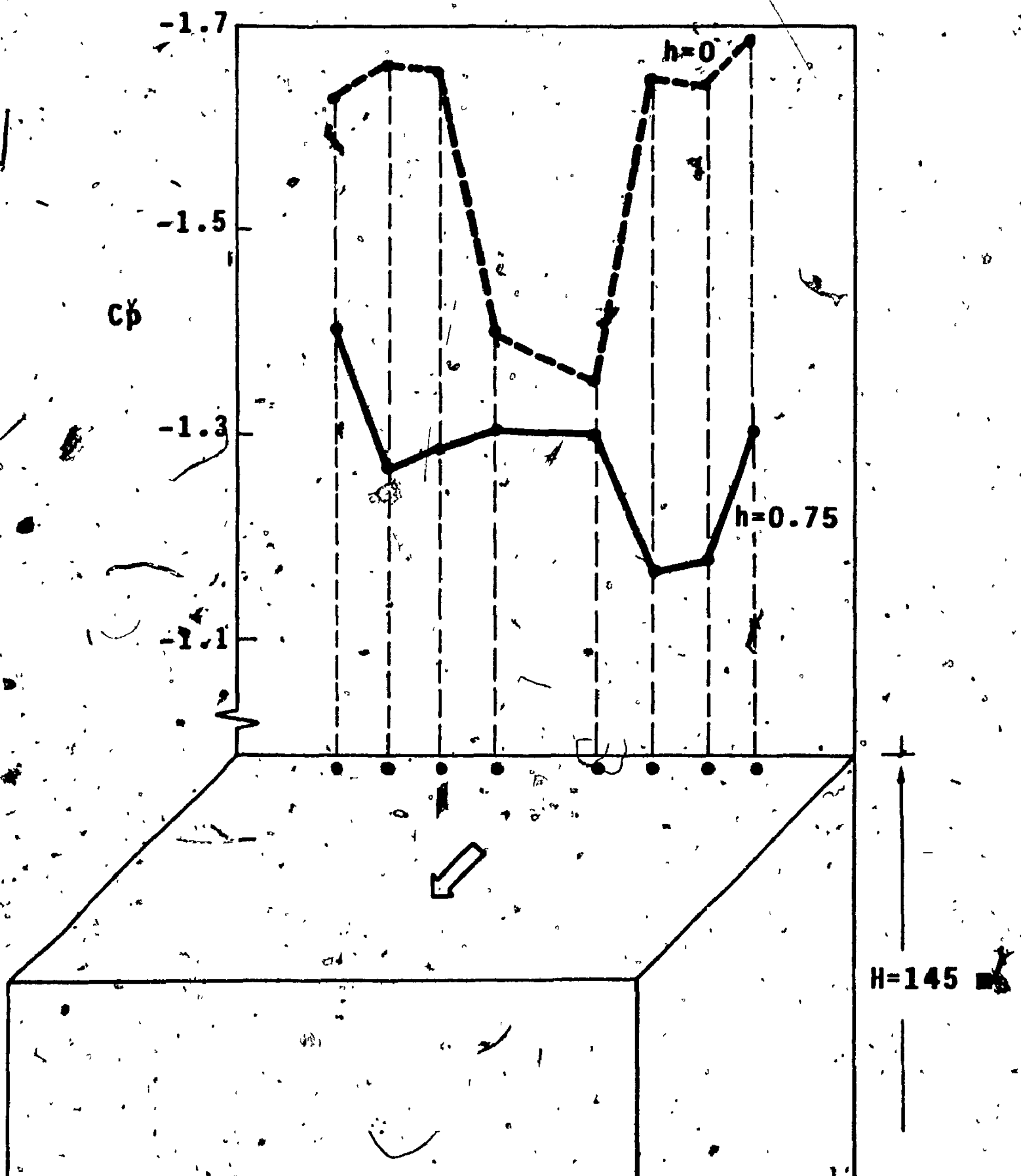


FIG. 4.14a PARAPET EFFECT ON PEAK PRESSURE COEFFICIENTS FOR FLAT ROOF EDGES (OPEN COUNTRY)

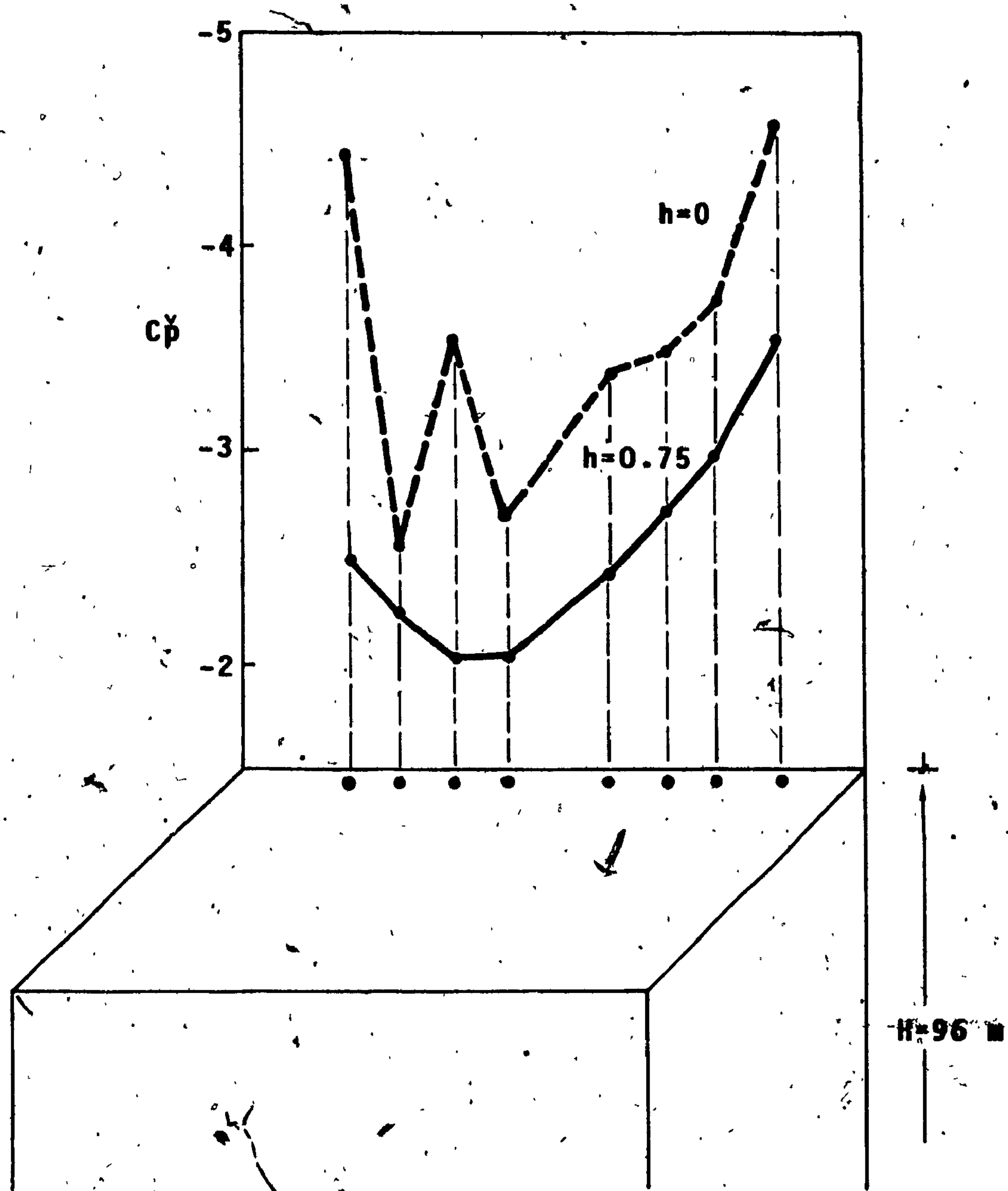


FIG. 4.14b. PARAPET EFFECT ON PEAK PRESSURE COEFFICIENTS FOR FLAT ROOF EDGES (URBAN)

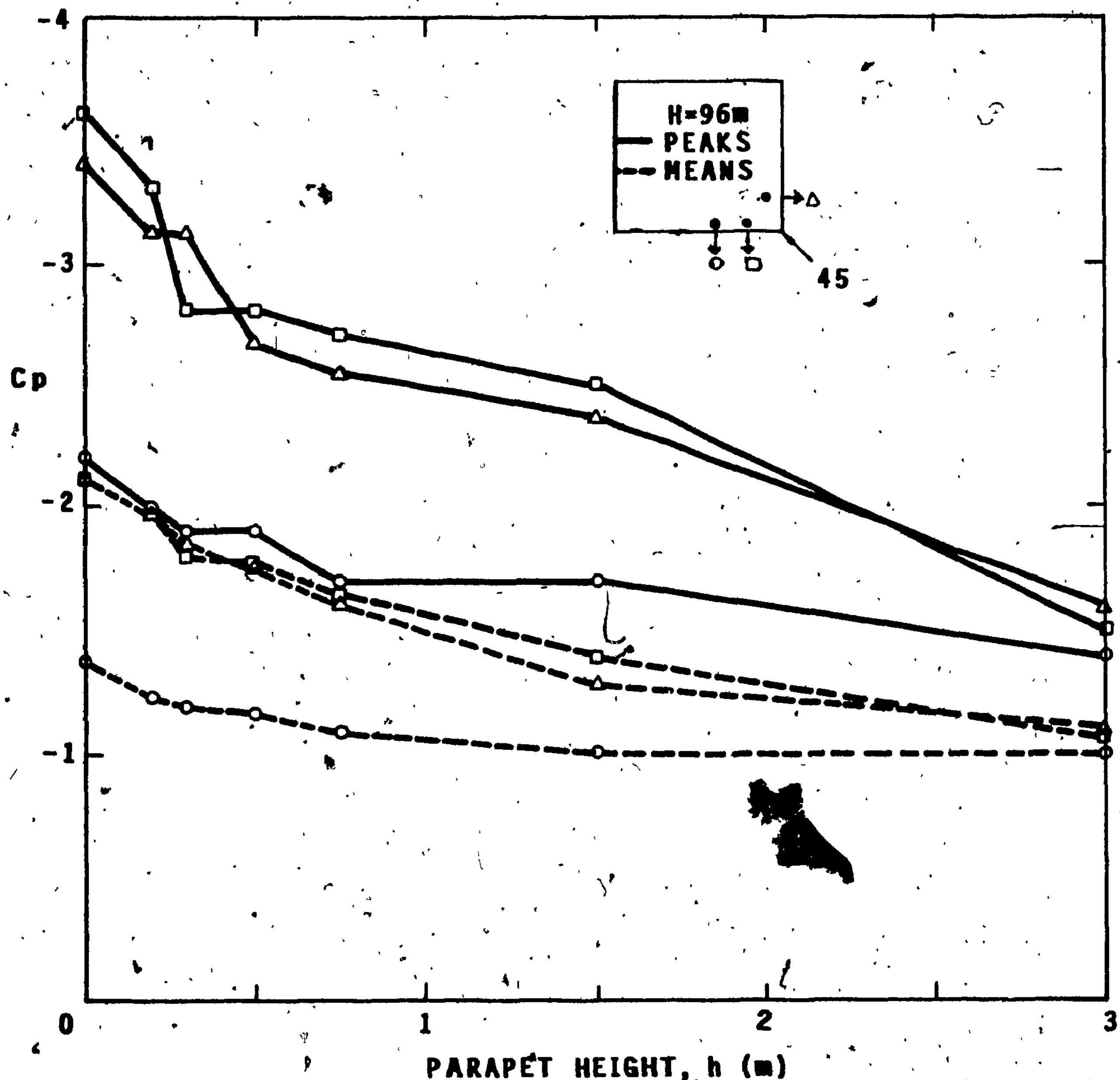


FIG. 4.15 THE EFFECT OF PARAPETS ON PRESSURE COEFFICIENTS FOR POINTS ON THE EDGES OF A FLAT ROOF FOR OBLIQUE WIND DIRECTION

P.V's represent increases of wind loads caused by the addition of parapets.

Typical results are shown in Fig 4.16. For each height of the building tested, the percentage variation was calculated using the pressure coefficient of the most critical wind direction. For each case the maximum value was dervied from all the taps that are located on the edge. Data of urban terrain results are also included in the figure. Data show that the percentage of variation is always positive for the peak pressure coefficients which implies that parapets reduce the wind suctions on roof edges. Generaly higher parapets cause larger reductions. This trend is well pronounced for tall buildings. However, some exceptions from the general pattern have been found for lower buildings. Additional experimental work carried out has confirmed the influence of parapets on low buildings.

The Percentage of Variation of mean wind pressure is shown at the top Half of the Fig. 4.16. The behavior of means is similar to that of the peaks except for some negative P.V 's (ie increase of wind loads caused on the roof edges by parapets) for the lowest buildings.

Different combinations of tributary areas are considered on roof edges (as shown in Fig 3.7) for the measurement of

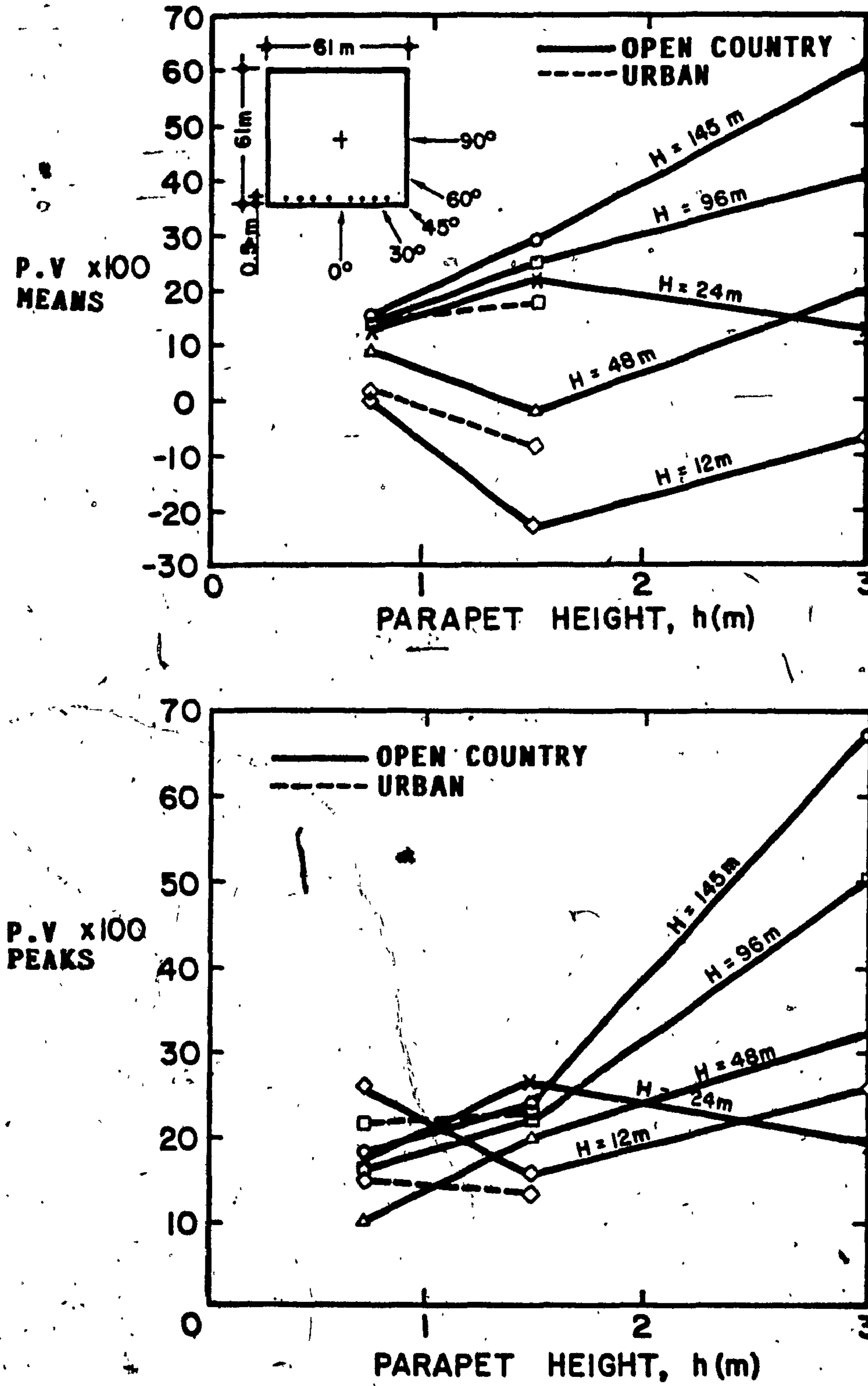


FIG. 4.16 PERCENTAGE VARIATION OF PRESSURE COEFFICIENTS ACTING ON ROOF EDGES FOR ALL PARAPET HEIGHTS

area-averaged loads. Figure 4.17 shows mean and peak uplift data for all heights of building tested. The worst uplift pressure coefficients have been presented for each parapet by selecting the maximum value from the various tributary areas tested on the roof edges for five wind directions. Both the mean and peak pressure coefficients are always reduced by the addition of parapets and these reductions are rather independent of parapet height.

Area-averaged Cp peak values are significantly smaller than corresponding local values measured inside the area of the roof regardless of parapets. For example, the area-averaged peak pressure coefficient on the edge of the tallest (145m) building without parapet is 1.7. The same building gives a local Cp peak of 3.8 (maximum among all point pressures on this particular edge). The implication is that a great overestimation of peak total load could be made if point pressure measurements were generalized over an area. Since parapets generally reduce the fluctuations on the heavily loaded roof edges, this difference between local and area-averaged loads may become more critical for roofs with parapets.

4.6 WIND LOADS ON ROOF CORNERS WITH PARAPET

This section will deal with the changes of roof corner wind

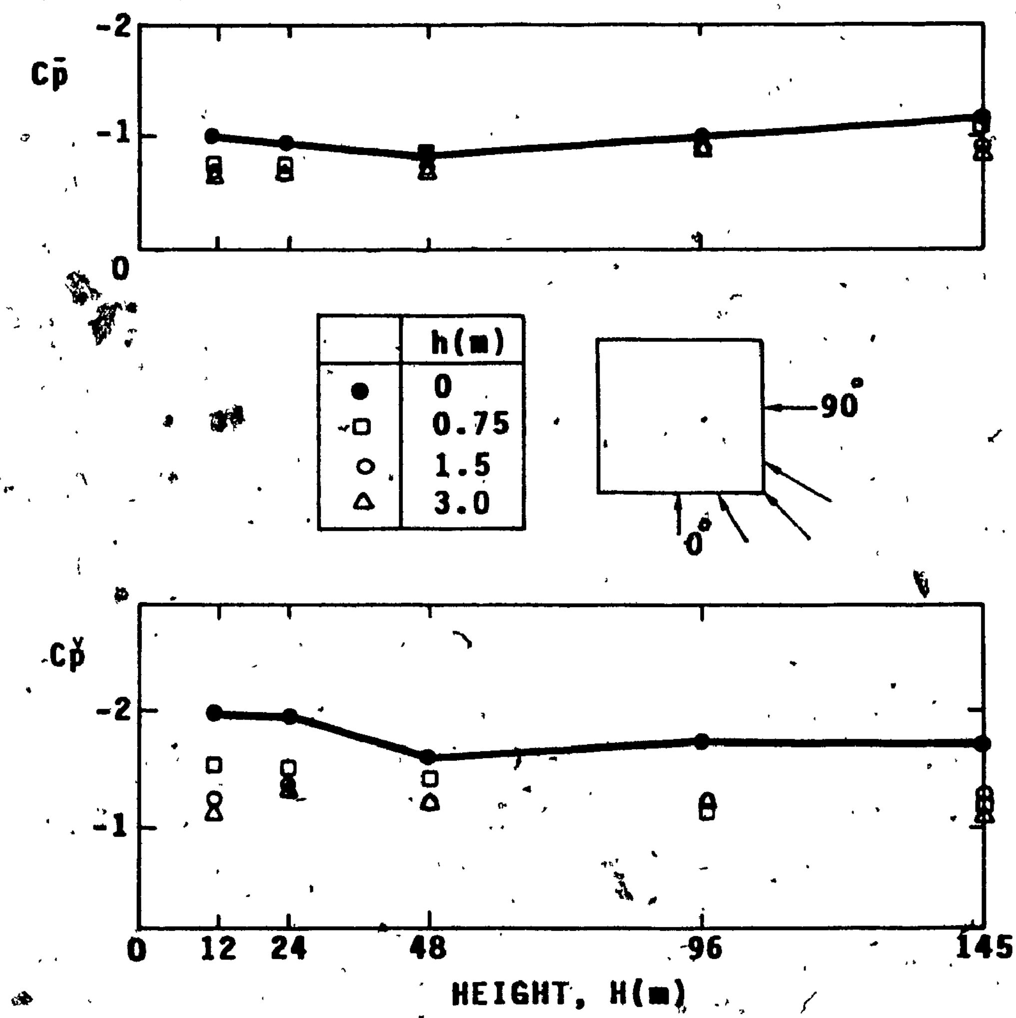


FIG. 4.17 MOST CRITICAL AREA-AVERAGED PRESSURE COEFFICIENTS FOR FLAT ROOF EDGES

loadings caused by the addition of parapets. Regardless of the existence of parapets the highest economical losses due to wind action occur on building roof corners for oblique wind directions, where the magnitude of load is maximum.

Some previous studies (5,9,17,20,et al.) have found that the corner loads are reduced significantly due to parapets. However, some recent work in this topic (24,38,49) has also found that the effects of parapet on roof corners may be different. Table, 4.1 presents all available literature data on the effect of parapets on pressure coefficients appropriate for roof corners. Only time-averaged (mean) pressure coefficients are tabulated mostly for cornering direction of the wind.

Leutheusser's study (22) reports that wind pressure becomes more severe on low buildings with low parapets but this seems to conflict with his results presented in the form of contours (see Figure 2.1). Scruton (34) states that for a hyperbolic paraboloid roof the corner pressure coefficient reduces from -5.5 to -0.6 by the addition of a 0.3 m parapet. However, these results originate from tests carried out under uniform flow conditions and they may not be appropriate if one considers the actual wind flow in the natural environment.

CORNER REGION

SCHOLAR	REF.NO.	FLOW	PARAMETERS	—Cβ (Mostly at 45)		
				NO PARAPET	LOW PARAPET	HIGH PARAPET
LEUTHEUSSER	22	UNIFORM	H/B=1;L/B=1 h/H=1/48,1/6	2.1	0.7	0.5
"	"	"	H/B=2;L/B=2 h/L=1/24,1/12	3.5	1.2	0.7
SCRUTON	34	"	*** h=0.3m	5.5	0.6	***
COLUMBUS	5	"	H/B=1/2;L/B=1 h/H=1/12	3.5	1.4	***
"	"	TURBULENT	H/B=1/2;L/B=1 h/H=1/12	2.0	2.3	***
KIND	17	"	H=4.8m h=0.45,1.4m	***	2.5	2.0
KRAMER	21	"	H/B=1;L/B=1 h/B=0.01,0.02	2.9	1.9	0.8
SOCKEL	37	"	H=70.5m L/B=1	2.5	***	1.1
"	"	"	h=1.4m L/B=2	2.9	***	1.2
STATHOPOULOS	38	"	H=5m L/B=1.5 h=1.2m	1.1	***	1.7
"	"	"	H=10m	1.4	***	1.9
SURRY and LYTHE	24	"	H=12m L/B=2 h=1.2,4.8m	0.8	1.1	0.8
"	"	"	H=30m	1.4	1.4	1.0
"	"	"	H=150m	2.5	1.5	0.9

NOTE:
1) *** data not available
2) low parapet < 1.0 m
3) high parapet > 1.0 m
4) local load coefficients are considered

TABLE 4.1 DATA FROM PREVIOUS STUDIES ON THE EFFECT OF PARAPETS ON ROOFS

Sockel and Taucher (37) did experiments on roof corners in turbulent flow using a parapet of 1.4 m on a tall building, they found that this parapet reduced the mean pressure by about 50 %. Other early studies in turbulent flow conditions (17, 21 et al.) also brought forth that parapets reduce the wind loads on roof corners. Recently, Stathopoulos (38), 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 and also the study by Lythe and Surry (24) has confirmed this findings. However, the inconclusive effect of parapets on tall building roof corners becomes evident from Table 4.1. It is, therefore, of interest to examine the effect of parapets on tall roof corners in detail.

The first attempt to study the local wind loading on roof corner of buildings with parapets was made by virtue of pressure tracings. Figure 4.18 shows such tracings for a tall building with low parapets. In each tracing the time duration corresponds to one hour in full scale. Examination of these tracings easily reveals that when the direction of wind is oblique the effect of parapets is more critical particularly for very low parapets. Several tracings have been procured for different building configurations. Tracings from roofs with parapets are compared with those from roofs without parapets in Fig. 4.19. Parapets on low

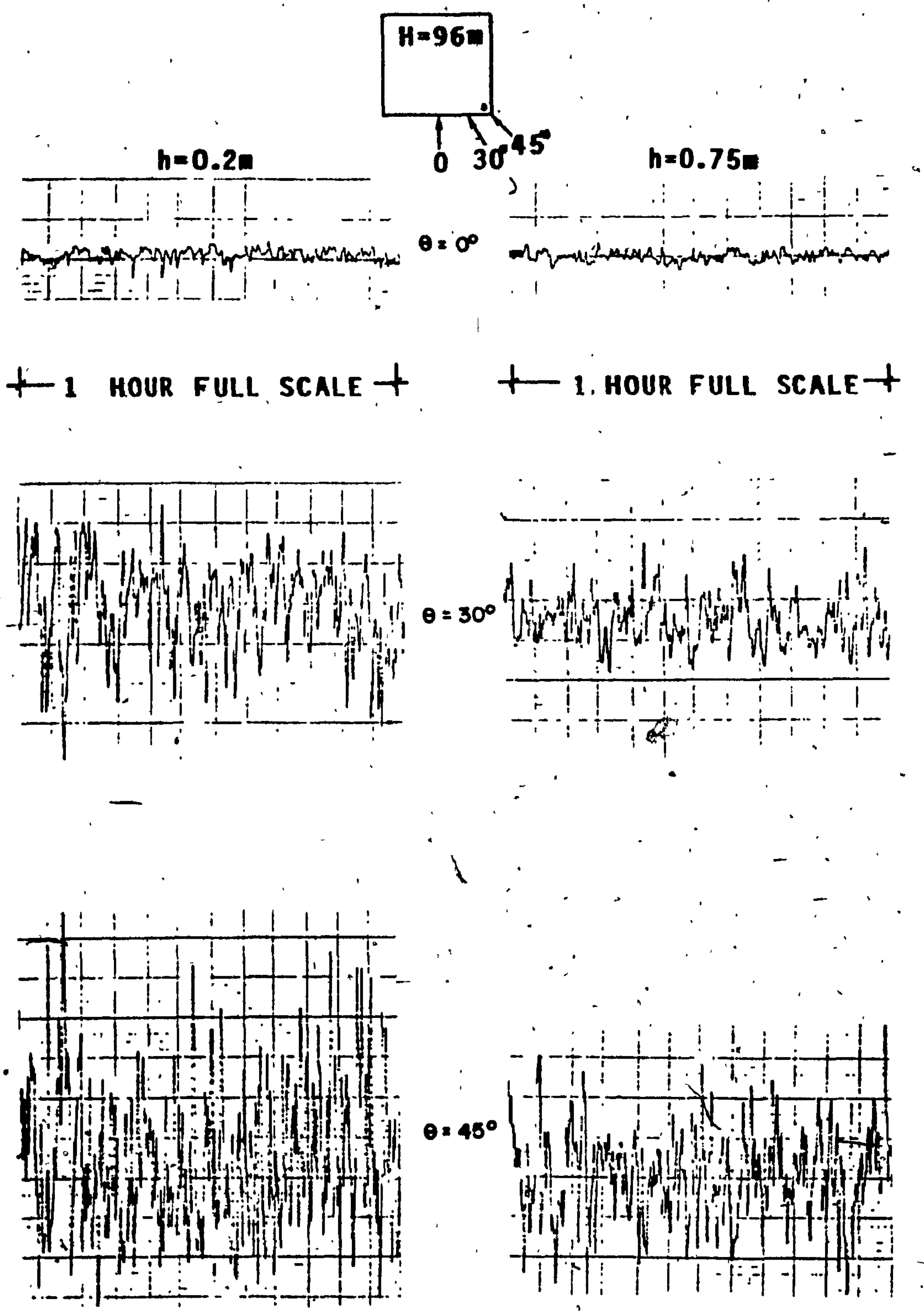


FIG. 4.18 EFFECT OF AZIMUTH ON WIND PRESSURE ON ROOF CORNERS WITH PARAPETS.

buildings increase the corner suctions whereas only parapets of height less than 1.0 m drastically affect the wind loading on the corner of tall building roofs. The given Cp values are referenced to the gradient height.

The variation of pressure coefficients with parapet height for all buildings examined is depicted in Figs. 4.20 and 4.21. Mean and peak pressure coefficients are presented for three different wind directions. Data indicate that pressure coefficients get their highest values mostly for the 45' wind direction. All parapets seem to increase the corner suctions in the case of lower buildings whereas only low parapets (less than 1.0 m high) have the same effect on tall buildings. It is also interesting to notice the variation of both mean and peak suction coefficients for very low parapets. This has been studied for two representative building heights (12 and 96m). Data indicate that the maximum suctions are obtained for a parapet approximately 0.4 to 0.5 m high.

Experimental results for the urban exposure are presented in Fig. 4.22. Mean pressure coefficients have comparable magnitudes with those found for open country exposure while peak pressure coefficients are approximately twice as large in urban terrain. This is caused by the increased turbulence of the flow, but it should be emphasized that the higher magnitude of peak Cp's does not necessarily

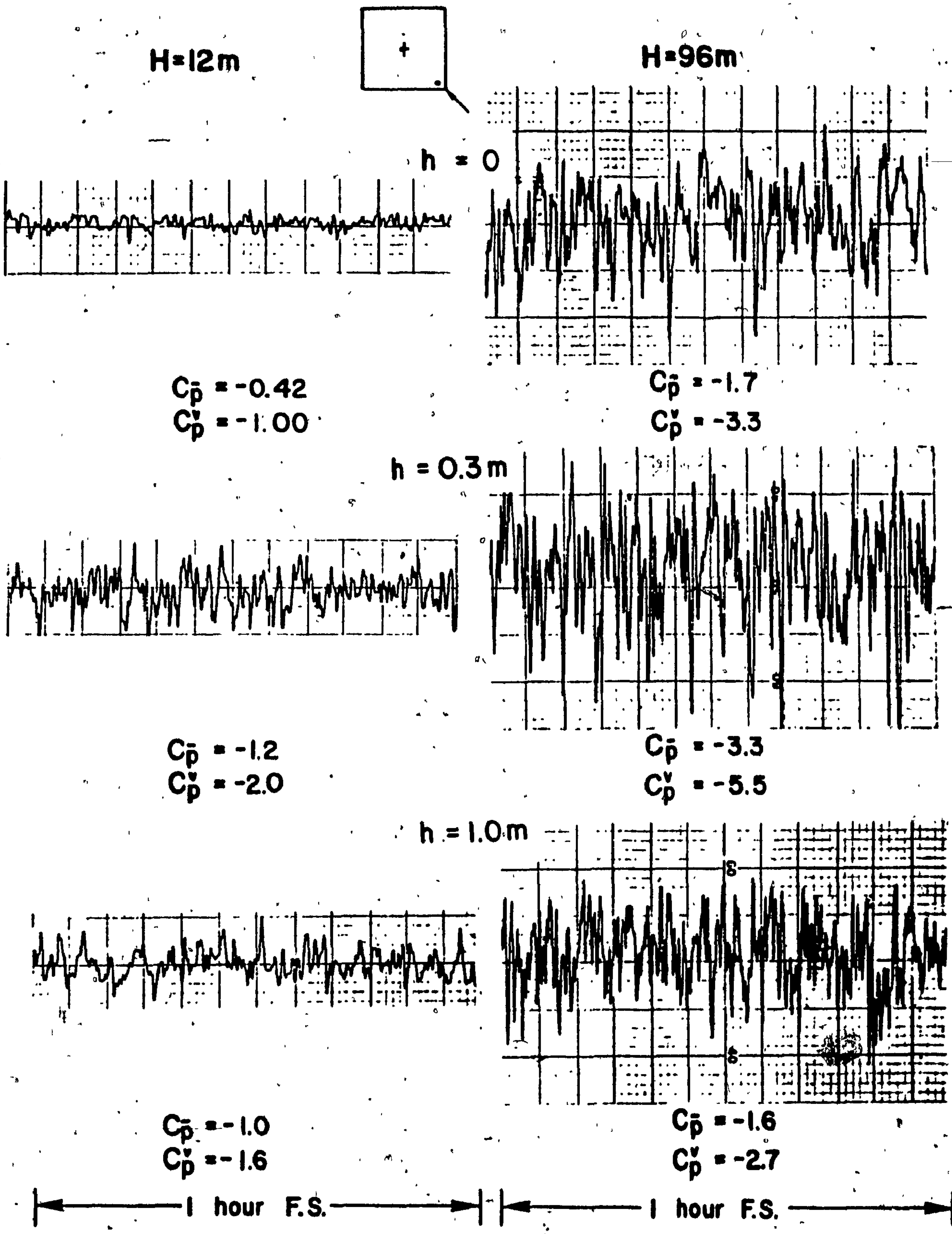


FIG. 4.19 EFFECT OF PARAPET HEIGHT ON WIND PRESSURE ACTING ON ROOF CORNERS FOR OBLIQUE WIND DIRECTIONS (45°)

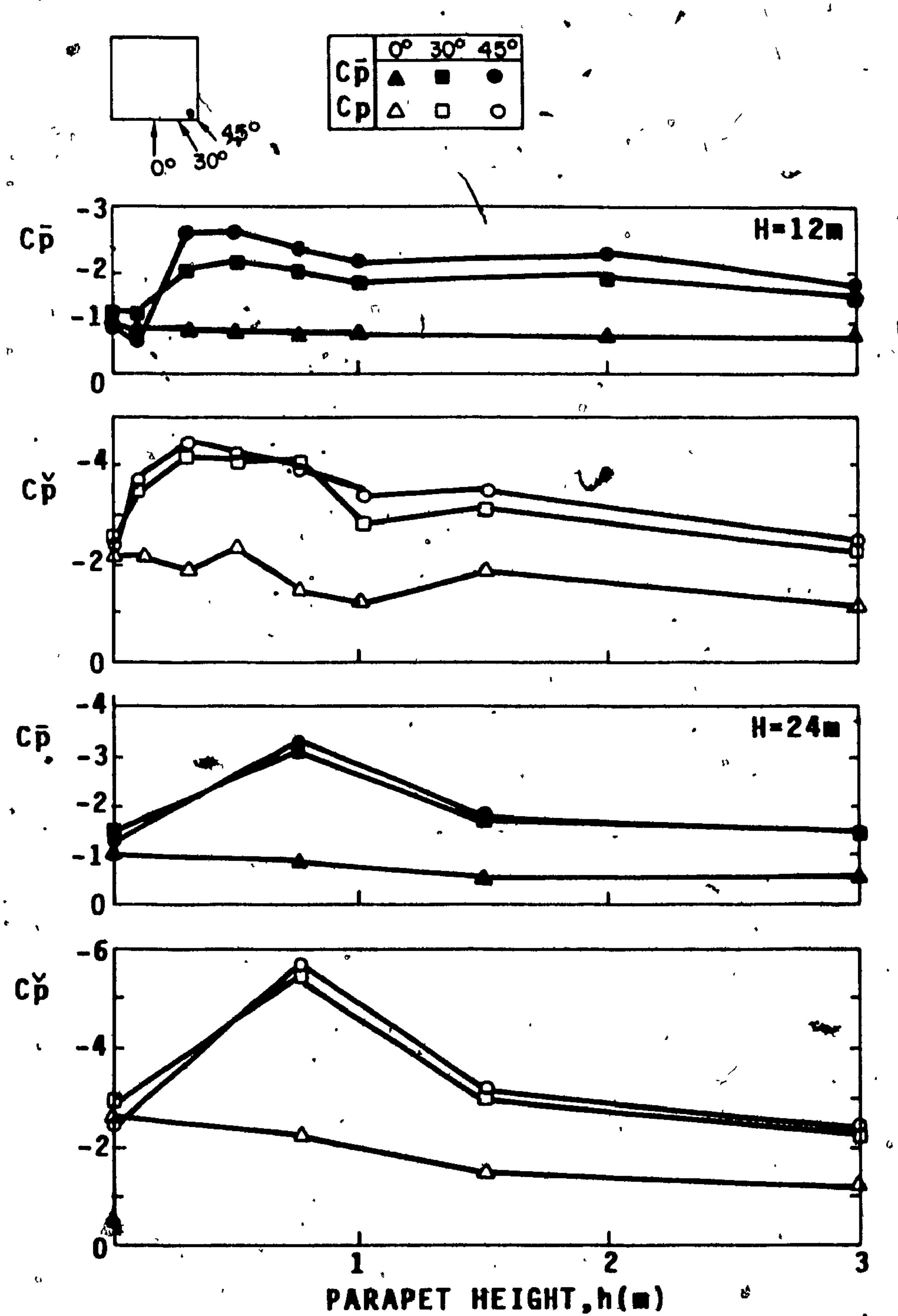


FIG. 4.20 EFFECT OF PARAPETS ON WIND-INDUCED PRESSURE COEFFICIENTS ACTING ON ROOF CORNERS (H=12,24m, OPEN COUNTRY)

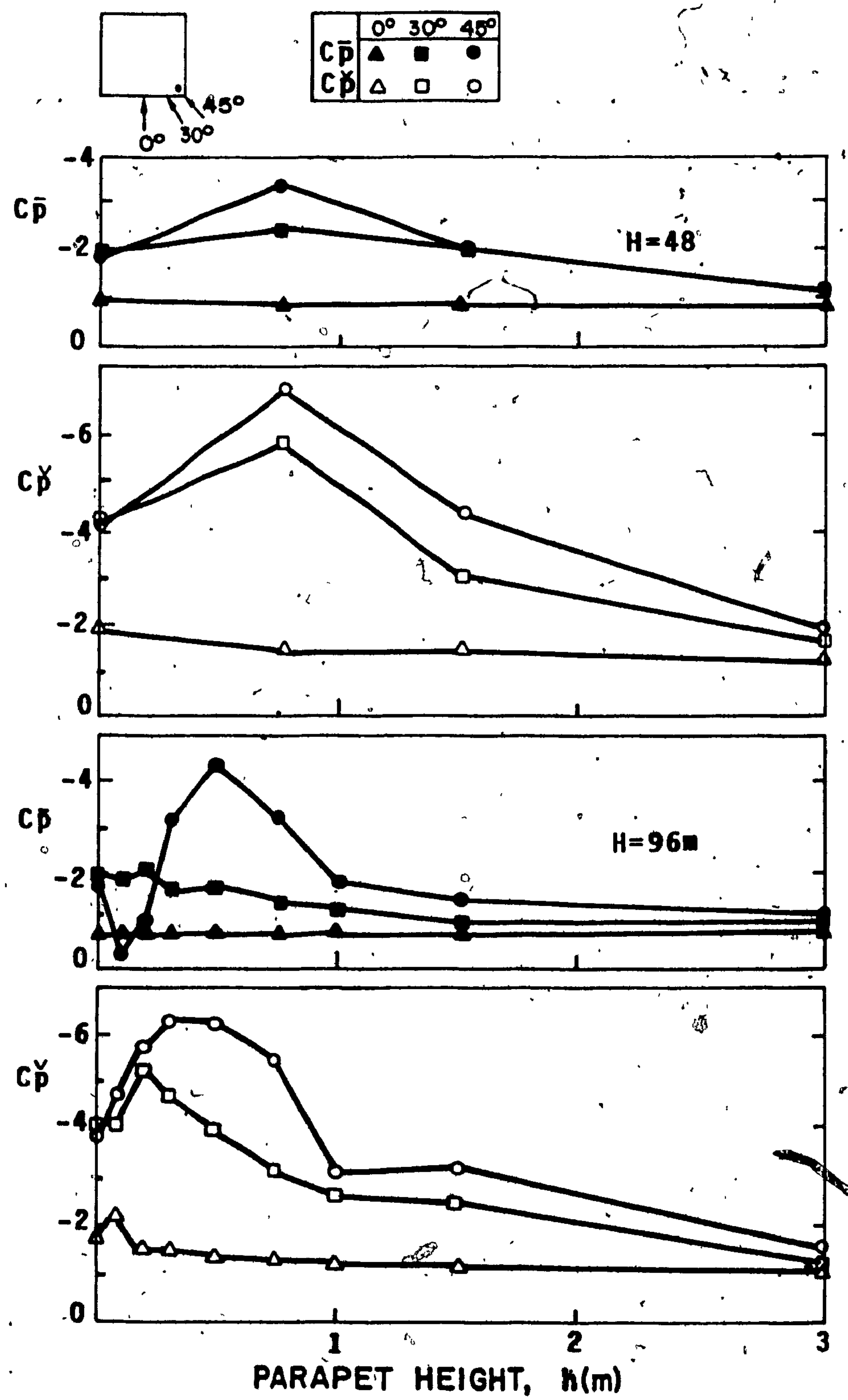


FIG. 4.21 EFFECT OF PARAPETS ON WIND-INDUCED PRESSURE COEFFICIENTS ACTING ON ROOF CORNERS (H=48,96m,OPEN COUNTRY)

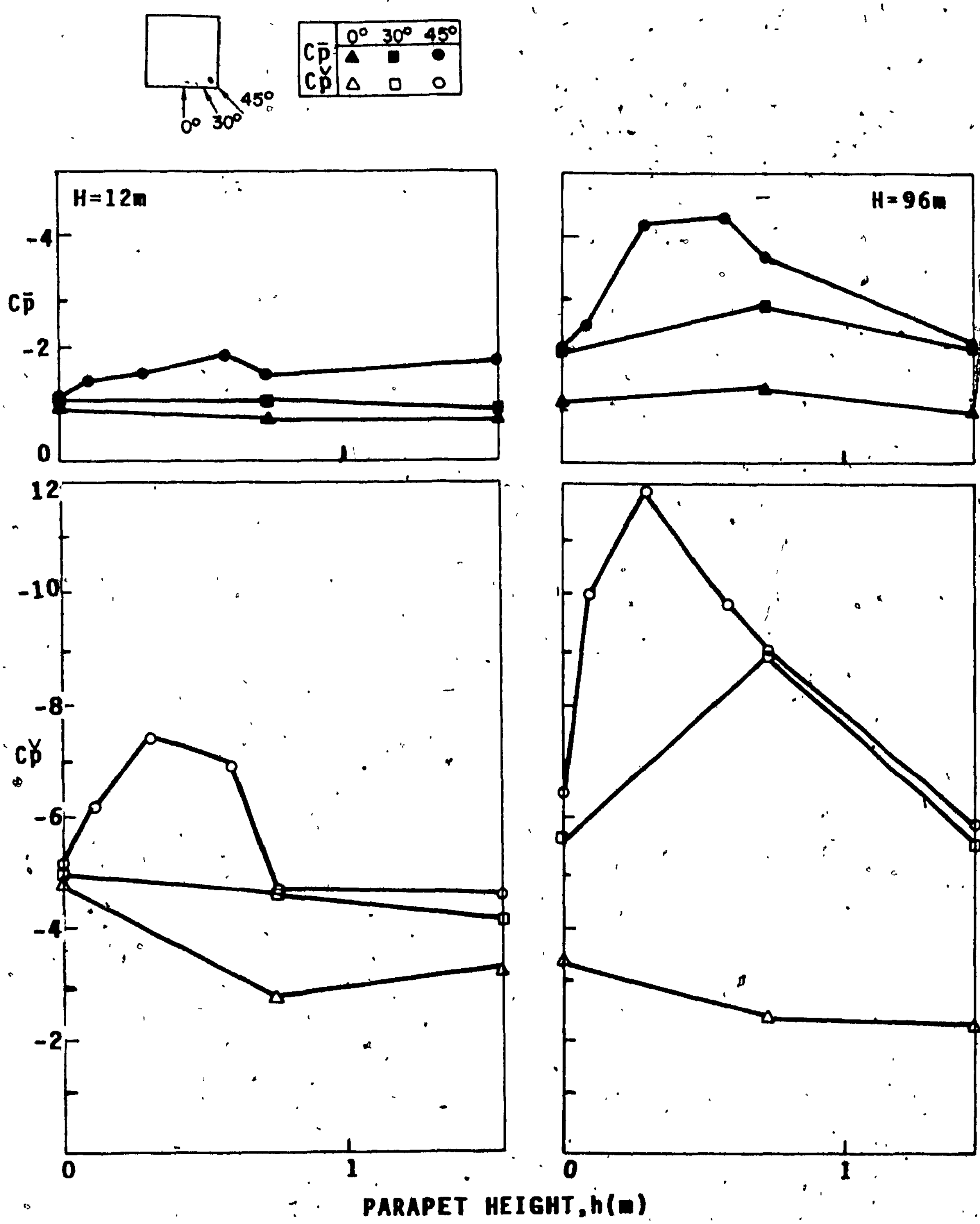


FIG. 4.22 EFFECT OF PARAPETS ON WIND-INDUCED PRESSURE COEFFICIENTS ACTING ON ROOF CORNERS (H=12,96m,URBAN TERRAIN)

imply higher suction loads on the roof corners. This is because these values are associated with a lower dynamic velocity pressure at roof height -- see the velocity profiles presented in Fig. 3.2. However, the influence of parapets on the corner suctions appears similar to that found in the open country terrain.

From the discussion it is clear that several peculiarities appear in the building roof corners equipped with different parapets. A simple indicative comparison is made in Figure 4.23, for all buildings tested in various terrain conditions. The most critical values of both mean and peak pressure coefficients measured from five wind directions for each parapet height examined are presented. Based on these data the following remarks can be made:

1) Roof corner pressure coefficients are increased by low parapets on any buildings in either open country or urban terrain exposure.

2) High parapets may reduce the wind suctions induced on roof corners of tall buildings.

The cause of this behaviour of pressure coefficients on roof corners of building with parapets will be discussed later in light of some spectral analysis data and further investigation.

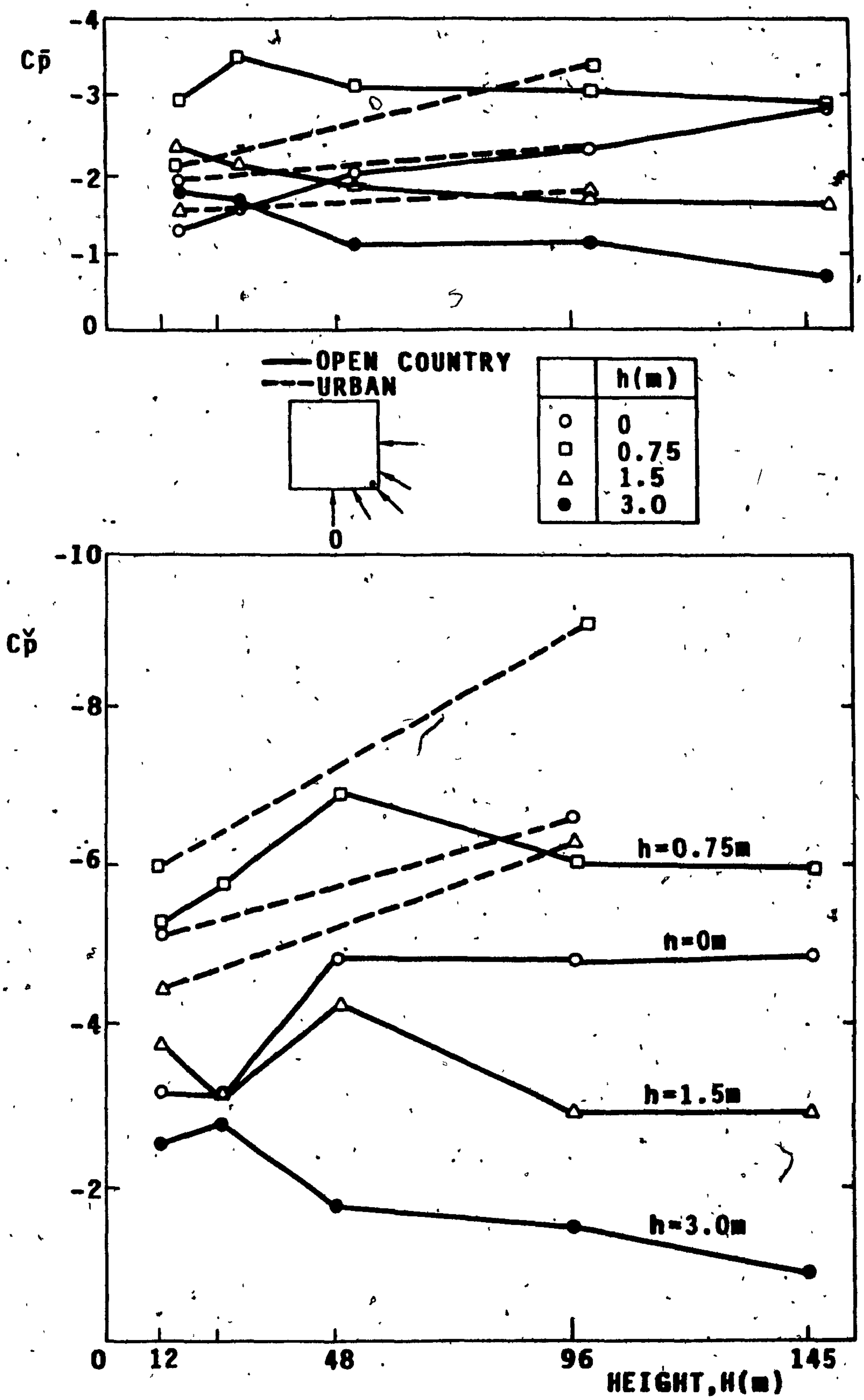


FIG. 4.23 MOST CRITICAL PRESSURE COEFFICIENTS MEASURED ON ROOF CORNERS

Area-averaged pressure coefficients collected for different buildings are presented in Figs. 4.24 and 4.25. The size of the corner area was selected according to the National Building Code of Canada (NBCC) provisions. Since, the 24m height belongs neither to low buildings nor is in the category of high buildings, both a square area (as shown in the 12 m roof) and an L shaped area, appropriate for taller buildings, are tested and the most critical effect is presented here. Pressure coefficients for three wind directions are shown. Similarly to the results obtained for local loads, low parapets on tall buildings and any parapets on low buildings generally increase the wind load on roof corner areas. This increase becomes worse for oblique wind directions.

Figure 4.26 shows the most critical area-averaged pressure coefficients measured for roof corners with parapets. Generally speaking, the trend is the same with that of local loads. By comparing Figs. 4.23 and 4.26 it is also interesting to note that the localized peaks show a significant reduction of magnitude when spatial averaging is taken into account regardless of the existence of parapets.

From the preceeding, it is very clear that low parapets in any building increase significantly the roof corner pressure coefficients for oblique wind directions. There is

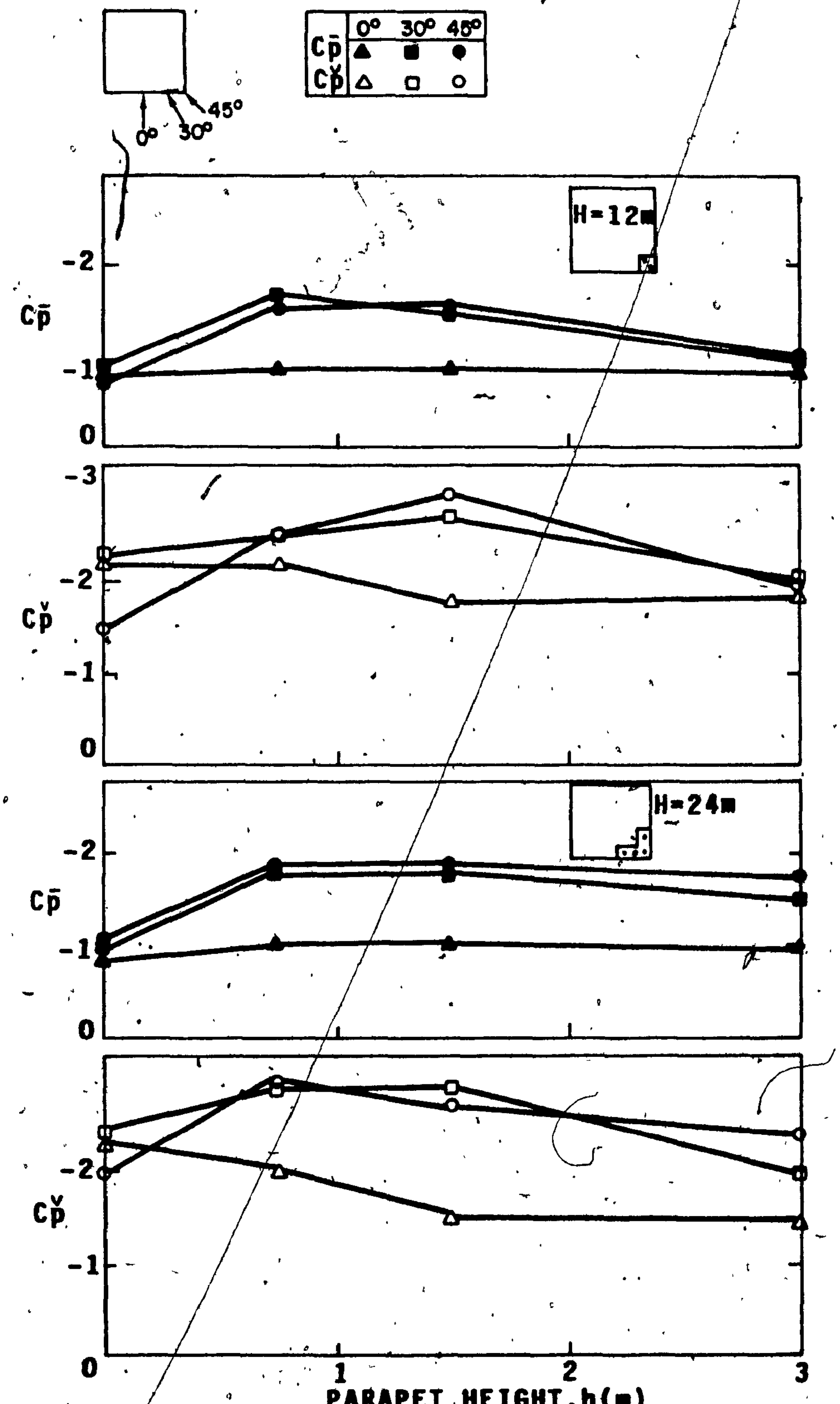


FIG. 4.26 AREA-AVERAGED PRESSURE COEFFICIENTS ACTING ON ROOF CORNERS WITH PARAPETS(H=12,24m,OPEN COUNTRY)

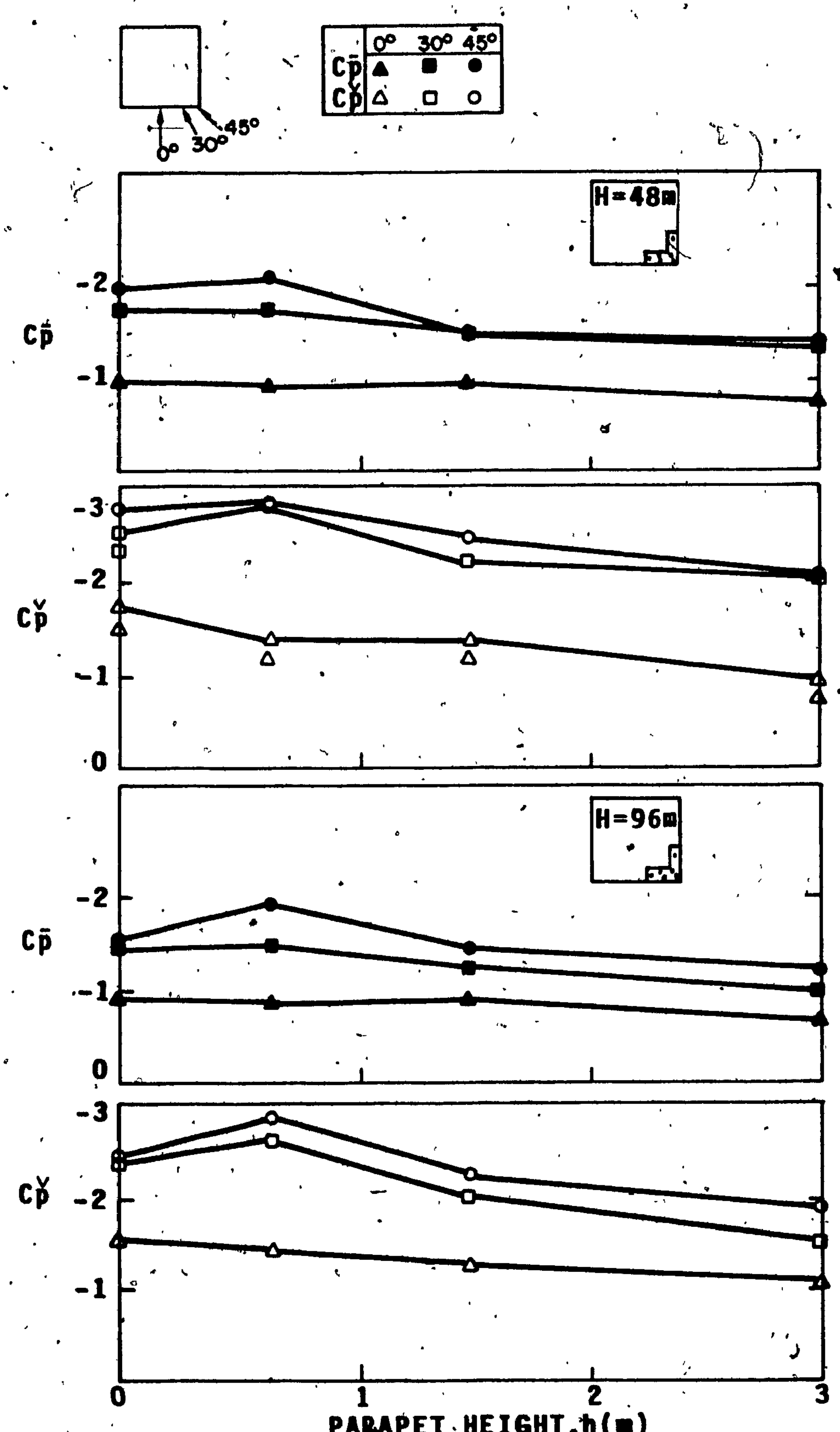


FIG. 4.25 AREA-AVERAGED PRESSURE COEFFICIENTS ACTING ON ROOF CORNERS WITH PARAPETS(H=48,96m,OPEN COUNTRY)

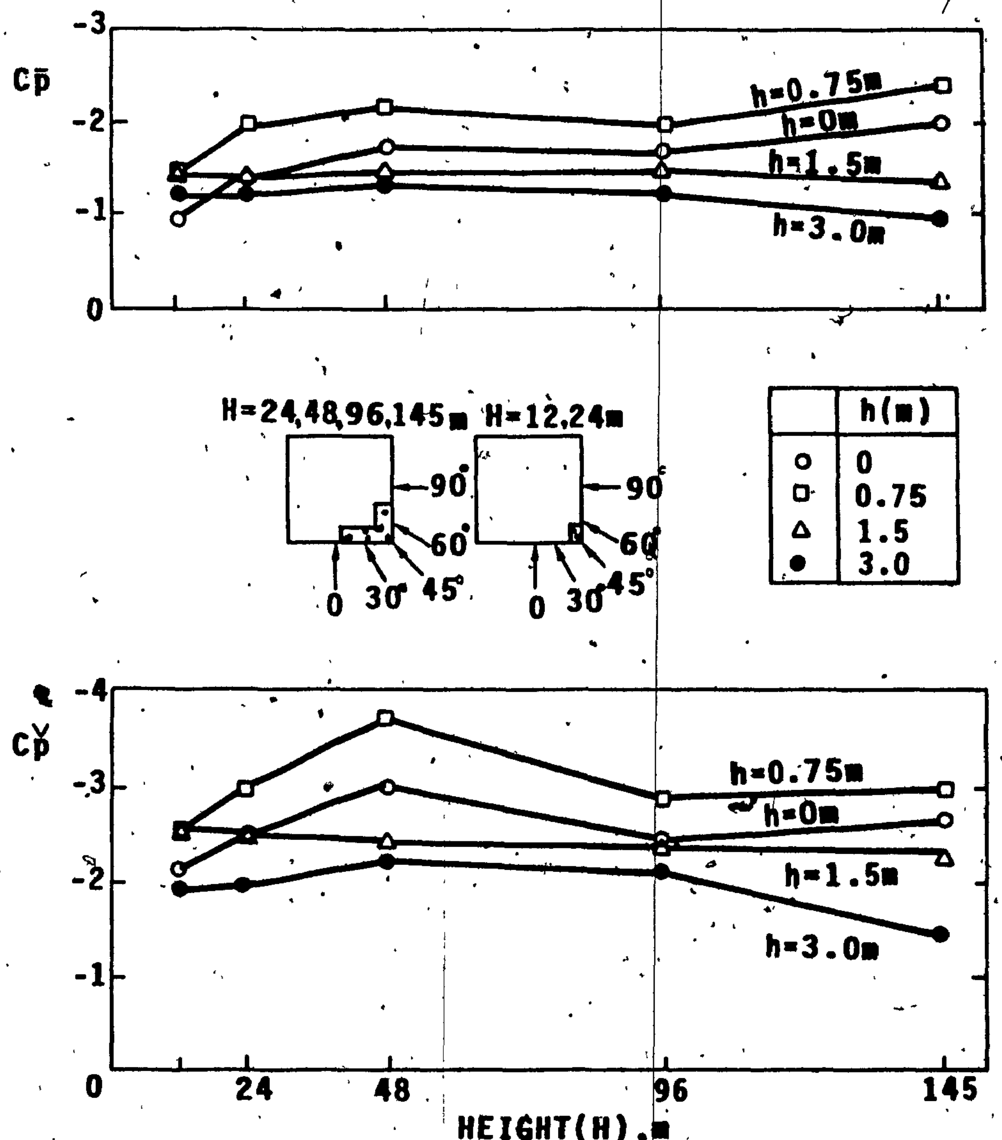


FIG. 4.26 MOST CRITICAL AREA-AVERAGED PRESSURE COEFFICIENTS MEASURED ON ROOF CORNER AREAS

no clear understanding of this behaviour of the wind when interacting with the building roofs with parapets. However, 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 a maximum at the corner. Small eddies may be produced in the vortex cones 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 are increased significantly. On tall buildings, the high parapets prevent the generation of small eddies in the vortex cones and act as a shelter for the corners by reducing the roof suctions. Further research work would be needed to understand this phenomenon in a better way. Wind tunnel studies on flow visualization also may provide useful information regarding wind interaction with building roofs with various parapets.

Power spectral density measurements have been made for different cases of roof corners with parapets. The Fast Fourier Transformation method (FFT) was used for the collection of spectral estimates. All spectra are normalized by the variance of the pressure. Hence the area under each spectral curve becomes unity. Each spectrum provides the energy associated with different frequency ranges. Hence the shape of the spectrum is characteristic of the nature of the random signal. A broad -banded spectrum shows the energy of a random process associated with a large range of frequencies. In contrast, a narrow-banded spectrum indicates that the major contribution in its energy is caused by a narrow band or particular frequency of turbulence.

As previously discussed, the parapet effect on roof corners is more critical for oblique wind directions. Therefore power spectral densities of pressure loads are drawn for oblique wind in the open country exposure.

Results are organized per building height in Figs. 4.27 to 4.30. In all cases the effect of parapet is apparent in decreasing the frequency associated with the highest energy content of the fluctuating pressure. This indicates a stabilizing effect that the parapet causes on the pressure fluctuations associated with the roof corners. This stabilization will be more effective in the case of higher parapets on tall buildings which tend to break the high frequency eddies of the pressure field into more stable eddies of lower frequency content.

Lower roof corners are exposed to a larger gradient of the wind speed as compared with taller buildings, which in turn are affected by a smaller turbulence intensity. This is probably the reason why there is less, high frequency energy content in the pressure fluctuations on the corners

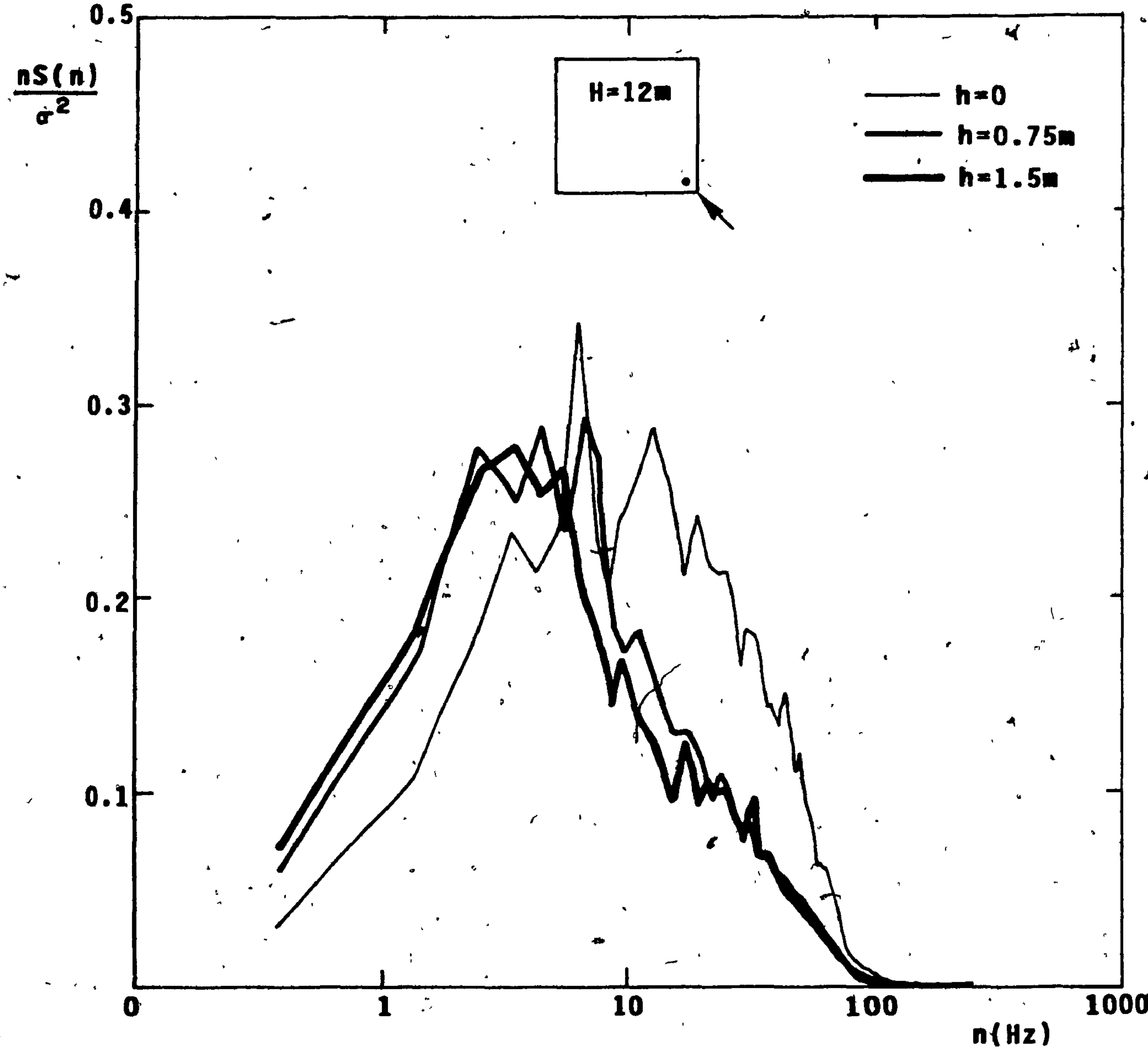


FIG. 4.27 POWER SPECTRA OF PRESSURE FLUCTUATIONS ON A CORNER POINT OF A FLAT ROOF WITH AND WITHOUT PARAPETS (OPEN COUNTRY EXPOSURE) H=12m

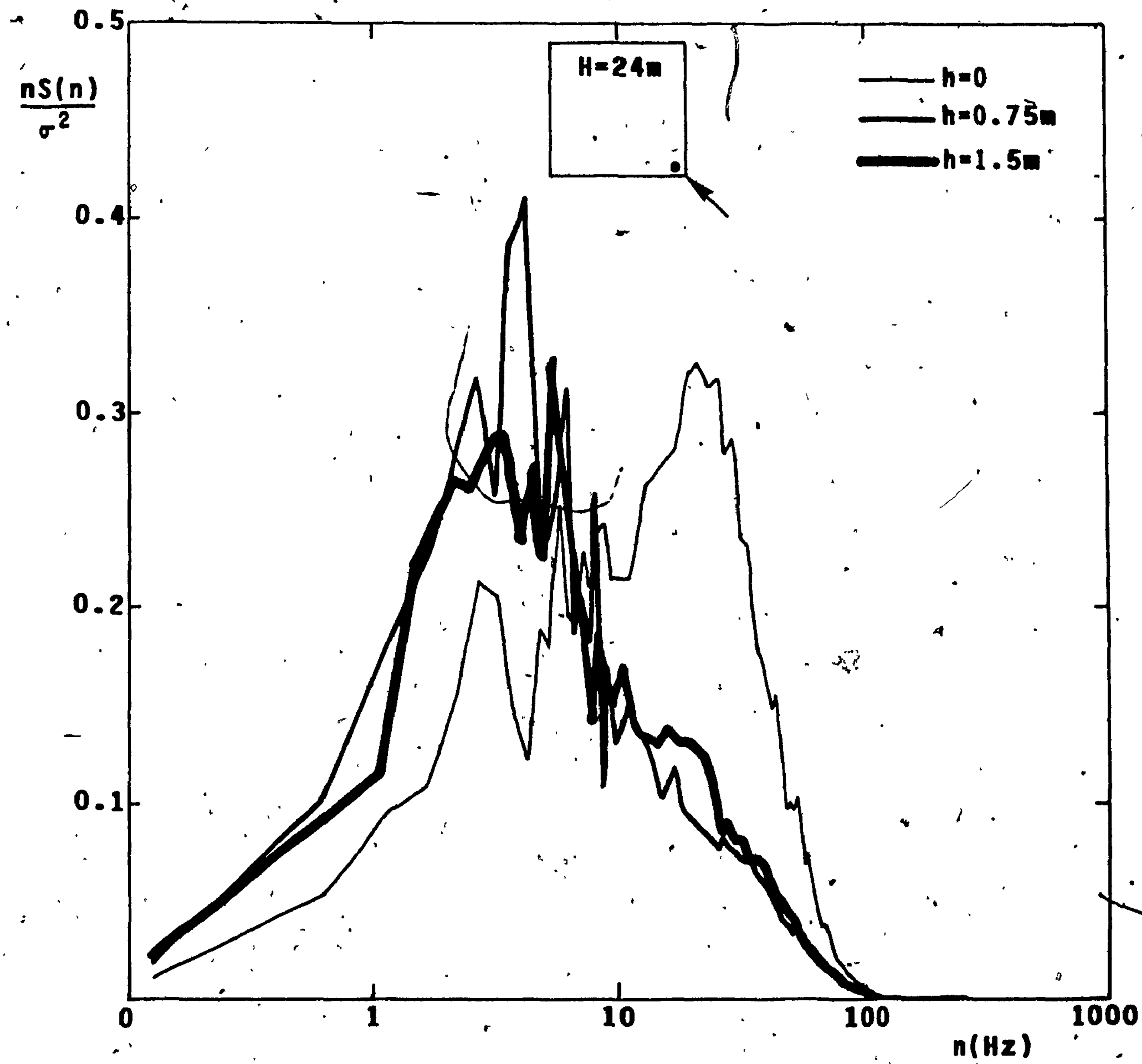


FIG. 4.28 POWER SPECTRA OF PRESSURE FLUCTUATIONS ON A CORNER POINT OF A FLAT ROOF WITH AND WITHOUT PARAPETS (OPEN COUNTRY EXPOSURE)H=24m.

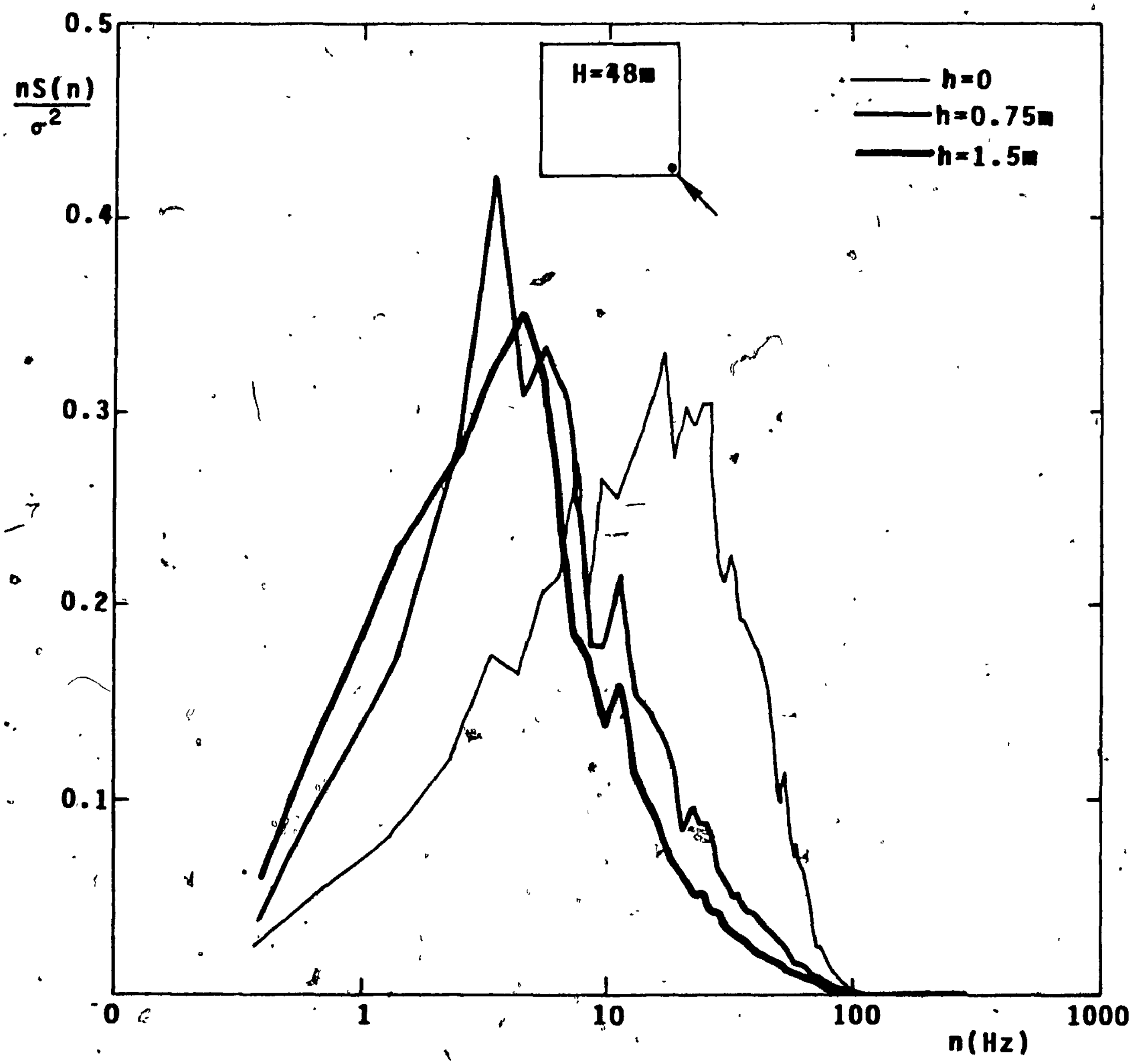


FIG. 4.29 POWER SPECTRA OF PRESSURE FLUCTUATIONS ON A CORNER POINT OF A FLAT ROOF WITH AND WITHOUT PARAPETS (OPEN COUNTRY EXPOSURE)H=48m

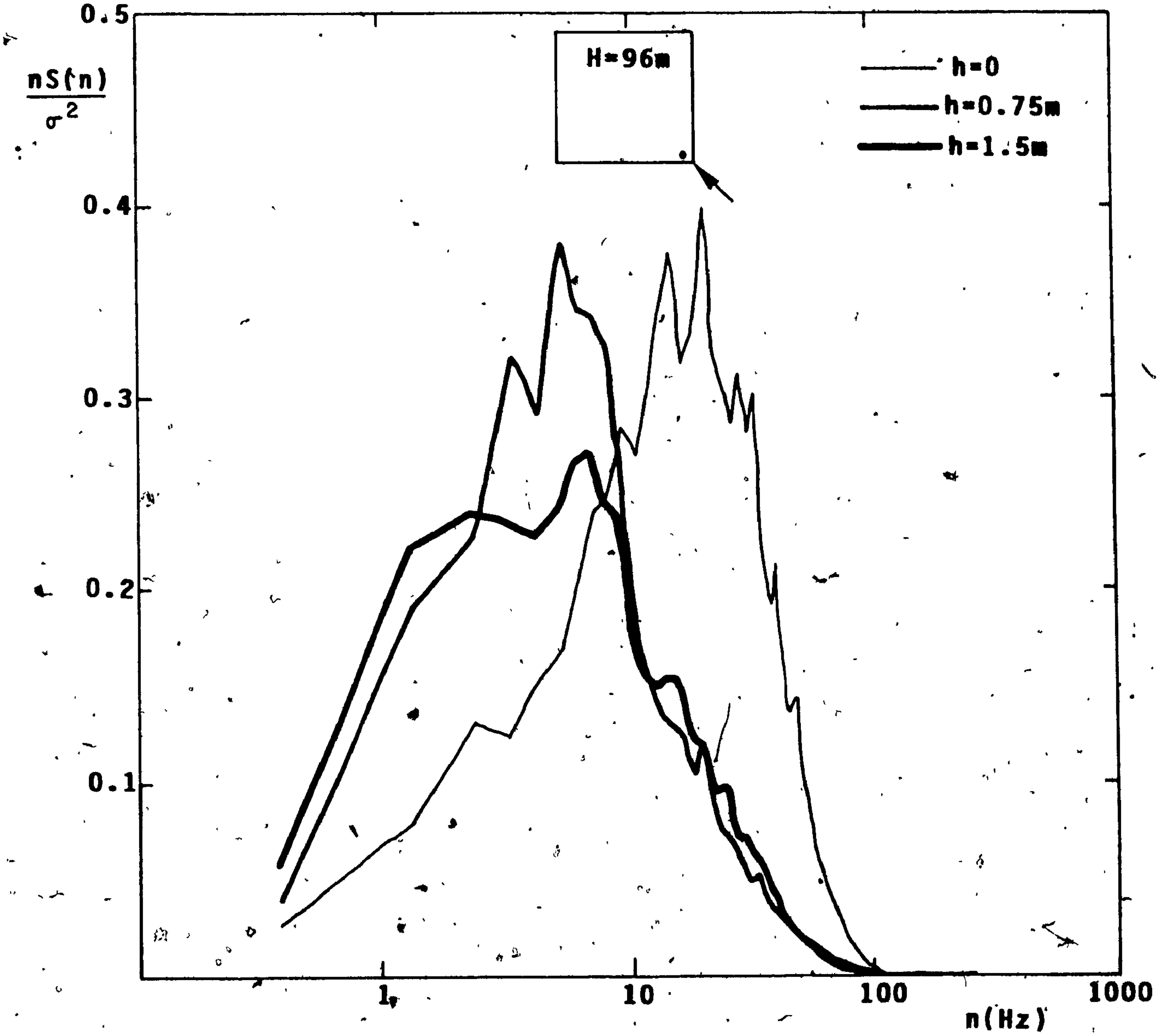


FIG. 4.30 POWER SPECTRA OF PRESSURE FLUCTUATIONS ON A CORNER POINT OF A FLAT ROOF WITH AND WITHOUT PARAPETS (OPEN COUNTRY EXPOSURE) H=96m

of tall buildings without parapets (steepest gradient of spectral curve of Fig. 4.30 in comparison with Fig. 4.27). Nevertheless, this difference tends to disappear in the case of buildings with parapets because of the domineering effect of parapets on the flow conditions.

CHAPTER 5

QUALITY ASSURANCE OF PEAK PRESSURE COEFFICIENTS MEASURED IN THE WIND TUNNEL

" The aim of statistical theory of extreme values is to analyse observed extremes and to forecast further extremes "

....E.J.GUMBEL

5.1 GENERAL

The wind-induced loading on building roofs is expressed as a function of pressure coefficients measured either full scale or in wind tunnels. Full scale measurements are expensive, time consuming and they can be carried out only for existing buildings. Therefore, there has been an increasing use of boundary layer wind tunnels as the design tool, particularly when pressure coefficients for Building Codes and Loading Standards are required.

Wind tunnel results can be trusted only if their quality is assured. Model wind tunnel studies generally refine the statistical estimates of loads and in most cases, reduce the level of uncertanity on load estimations. However, uncertainties still exist in wind tunnel data. They originate mainly from the quality of simulation of natural wind, the measurement techniques, the sampling rate used in digitization of the pressure signal and the frequency response of measuring system .

One random variable which needs particular attention in wind tunnel testing is the peak pressure coefficient. This issue becomes very important, since peak pressure coefficients are designated as design parameters by Codes and Standards. Peaks are random and the theory of Extreme Value Distribution (E.V.D) can be used for the estimation of peaks at a particular realiability level.

This process, however, is extremely time consuming and in most practical cases laboratories rely on single peaks acquired from a sufficiently long record. This procedure was also applied in the tests of the present study. A question therefore arises about the possible error expected in the estimation of peak Cp values for different building configurations (building height, parapet height, etc.). To this end, some particular cases have been examined in detail for comparison purposes. Before proceeding with these cases the fundamentals of extreme value distribution analysis are summarized.

5.2 EXTREME VALUE DISTRIBUTIONS (E.V.D)

An important class of probability problems are those involving the extreme value distribution of random variables. The summary presented here, is formulated from references 2 and 14.

The largest values from samples of size "n" are also random variables and therefore have probability distributions of their own. These distributions can be related to the distribution of the initial variate (or population). Because the extreme values of a random variable are invariably associated with the tails of its probability density function, the convergence of the distribution function of its extreme value to a particular limiting form, will depend largely on the tail behavior of the initial distribution in the direction of extreme. An exponentially decaying tail will converge to the Type-1 EVD form. This type has been found satisfactory for the prediction of peak presure coefficients and has thus been applied for the analysis of the present study.

The Cumulative distribution function (CDF) of the Type-1 form for the distribution of the largest value may be defined as :

$$F_X(x) = \exp\{-e^{-S}\} \qquad 5.1$$

where s = an(x-un) is the standard variate , un and an are the mode and dispersion parameters of the distribution.

By virtue of the relationship between the probability density function (PDF) and the cumulative distribution function (CDF):

$$f_X(x) = dF(x)/dx \qquad 5.2$$

where $f_X(x)$ is the PDF which can be written as:

$$f_X(x) = an[\exp^{-S}\{\exp(-\exp^{-S})\}] \qquad 5.3$$

An extremal probability graph may then be constructed with values of "s" scaled on one axis and the associated CDF given on the same (or parallel) axis. The other (perpendicular) axis represents values of the extreme variate. A straight line with a positive slope, therefore represents the largest value Type-1 EVD form .

5.3 APPLICATION OF PRESENT STUDY DATA

From the discussion of the previous chapter it is apparent that peak pressure coefficients have large values on roof corners with parapets for oblique wind directions. The roof corner region was then selected for more detailed study of peak pressure coefficients. Coefficients have been acquired in an open country flow regime. Pressure signals from an edge tap were also analyzed.

Data were acquired for a period of 15 seconds using a sampling rate of 500 samples per second. Statistical extremes may provide useful information provided that the sample size of the population is large. Therefore 50 records have been collected resulting to 375,000 samples of data for analysis. A point of concerns about these measurements is the large amount of time required for the collection of data. It has been observed that each set of data (50 records) requires approximately 4 hours of wind tunnel operation for one point of only one configuration (building height, parapet height, wind direction, exposure).

The pressure coefficients measured are referenced to the dynamic velocity pressure at the roof height level and for mathematical convenience all negative peaks are changed to their absolute values. They are ranked by magnitude so that the lowest of n values (n = 50 in the present study) is given the rank m=1, the second lowest m=2, and so on up to the highest m=n. The probability distribution may then be estimated from these ranks by the equation:

$$P(peaks) = m/(n+1) \qquad 5.4$$

The Type-1 reduced variate s can be estimated according to Equation 5.1 as follows:

$$s(peaks) = -\ln\{-\ln(P(peaks)\} \qquad 5.5$$

The PDF's is of the peaks are thus plotted by using Equation 5.3. The EVD lines may also be formulated by using the values of the extremes against their estimated s values.

The PDF curves and EVD lines are shown in Figures 5.1 and 5.2. respectively. Figures are arranged according to the building height. For each building, values are compared for the cases of with and without parapets. Two parapet heights, namely 0.75 and 1.5 m, have been examined.

The PDF shows the distribution of suction peaks occuring on the roof corner of buildings exposed to open country simulated wind conditions. The effective width of PDF generally decreases with increase in parapet height and this is more clearly identified for tall buildings. Mode values of the distribution, which are characterized by the maximum likelihood of occurence, confirm the results discussed in the previous chapter, regarding the effect of

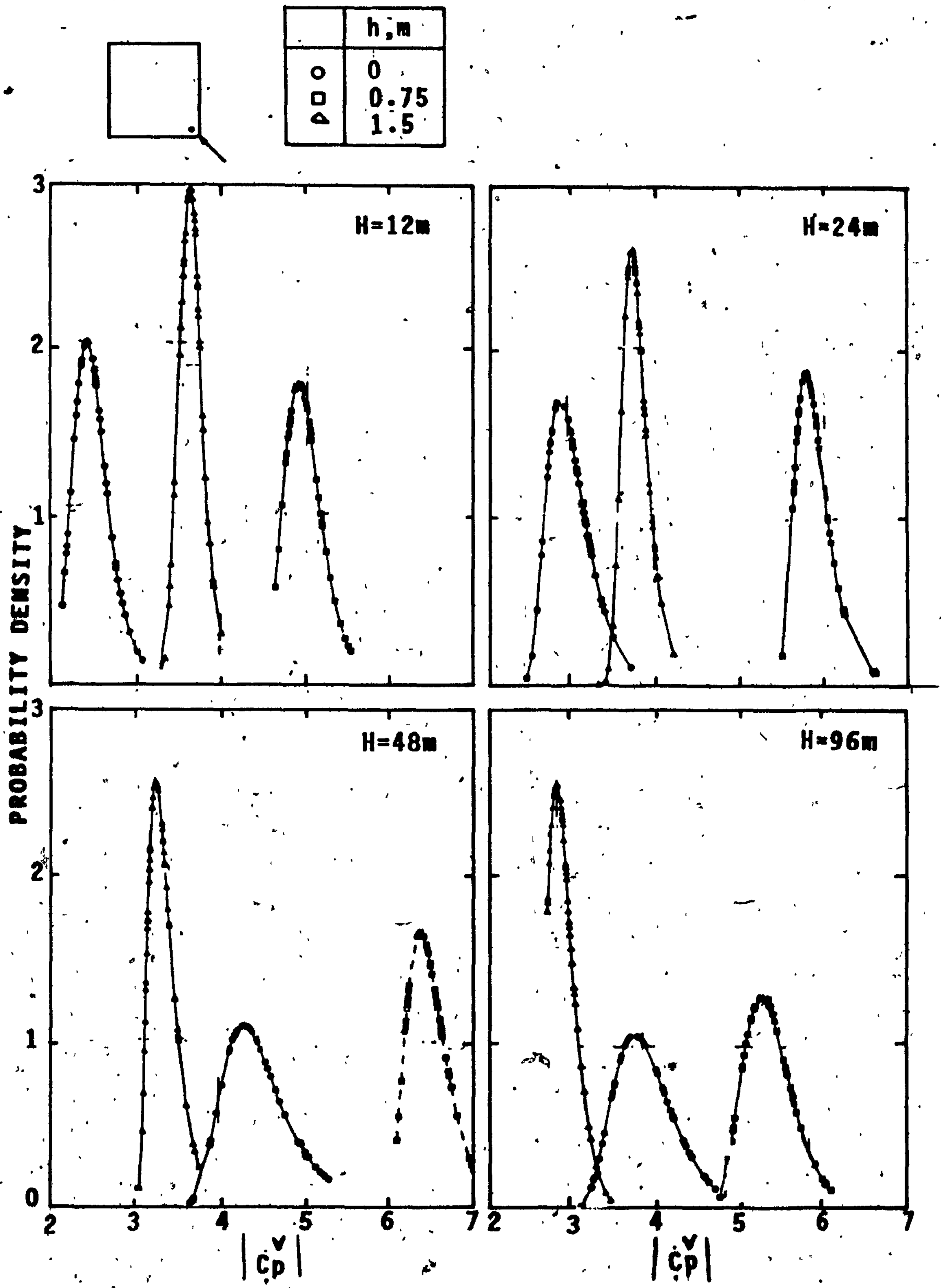


FIG. 5.1 PROBABILITY DENSITY FUNCTIONS FOR A FLAT ROOF CORNER WITH AND WITHOUT PARAPETS

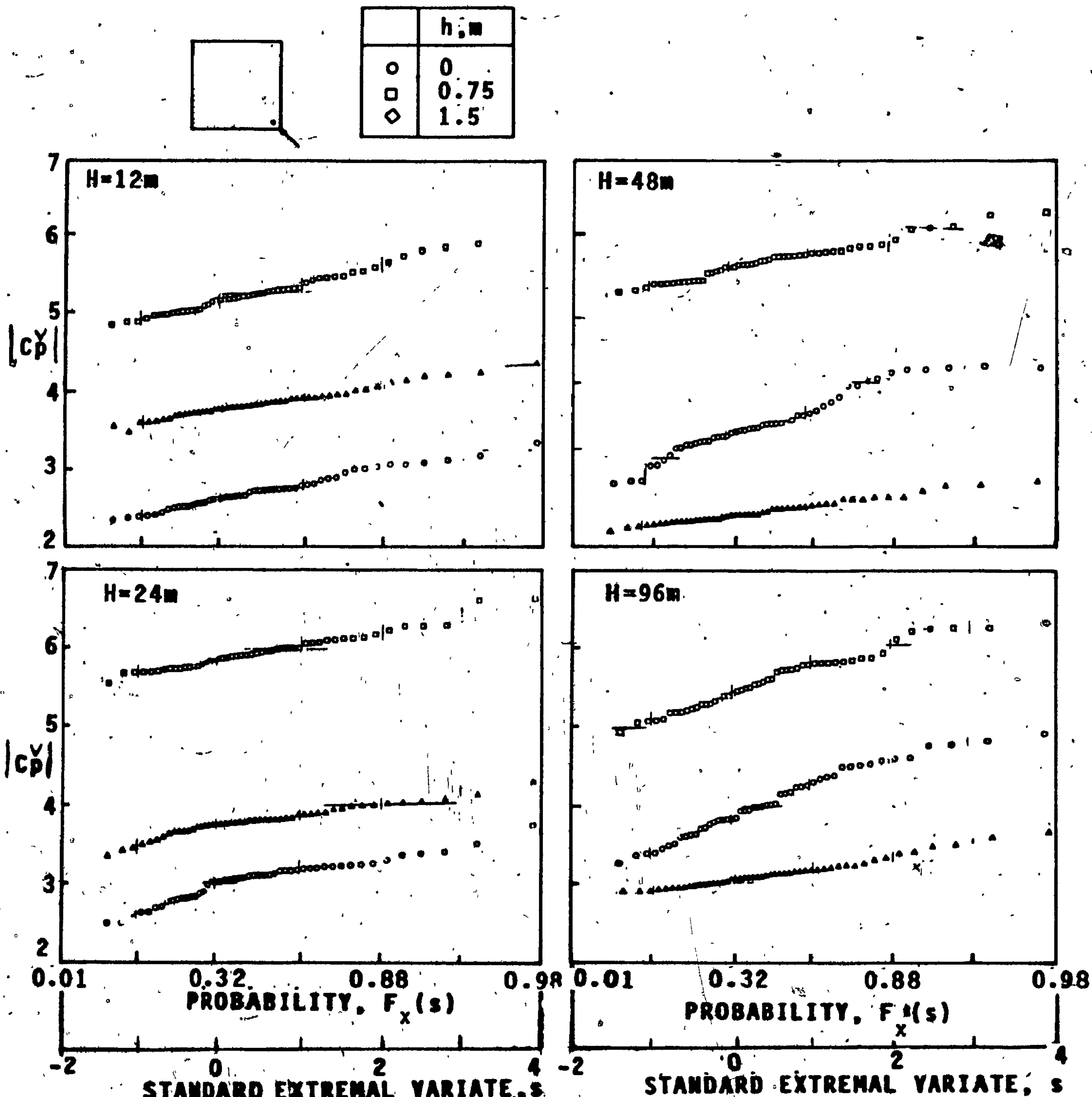


FIG. 5.2 EXTREME VALUE DISTRIBUTIONS FOR A FLAT ROOF CORNER WITH AND WITHOUT PARAPETS

parapets on roof corner suction loads. Also for lower buildings there is no overlapping between PDF's whereas on taller buildings some minimum overlapping is not significant. This indicates that it is statistically safe to consider peak suctions of a single record, at least for this particular case.

The EVD lines shown in Fig. 5.2 give the value of Cp peaks for certain predeterminted probability risk levels of exceedance. Fitting the best straight line to the data by the least square method (linear regression), the correlation coefficient was found to be greater than 0.97 for all the cases examined. As such the Type-1 EVD form appears indeed suitable and applicable for predicting the extreme suction peaks that are induced on roof corners with parapets. The probability of exceedance (P) or the return period of these Cp peaks can be predicted by using these lines. For example, the probability of peaks (H=96m, and h=0.75m) exceeding magnitude 6, is

$$
\begin{aligned}
P(\text{peaks} > 6) &= 1 - F_x(6) \\
&= 1 - 0.88 \\
&= 0.12
\end{aligned}
$$

Therefore, in accordance with the available data set, there is a chance of 88 % for the occurrence of peak pressure coefficient having value less than or equal 6, for this particular case. Similar types of evaluation can also be possible for other cases examined.

It has been considered desirable to compare the Cp peak values discussed in the previous chapter from a single record with those evaluated using extreme value distributions. Figure 5.3 presents the results for all buildings. Data indicate that the single record peak lies generally, close to the mode value of the peak measured by EVD. This trend of data enhances the quality assurance on the single - record peaks. Although results are presented only for two parapet heights, this observation has also been made for other cases.

To understand the effect of parapets on buildings of different height the PDF diagrams have been rearranged appropriately. Figure 5.4 shows the effect of building height for roofs without parapets. For tall buildings the effective width of PDF curves reflecting the range of measured values is comparatively wider than for low buildings. Therefore the reliability of suction peaks reported is higher for lower building. In addition, greater positive skewness for tall buildings indicates probability of occurence of larger peaks for these configurations.

The addition of parapets reduces both the range of measured peaks and the effect of building heights on roof corner

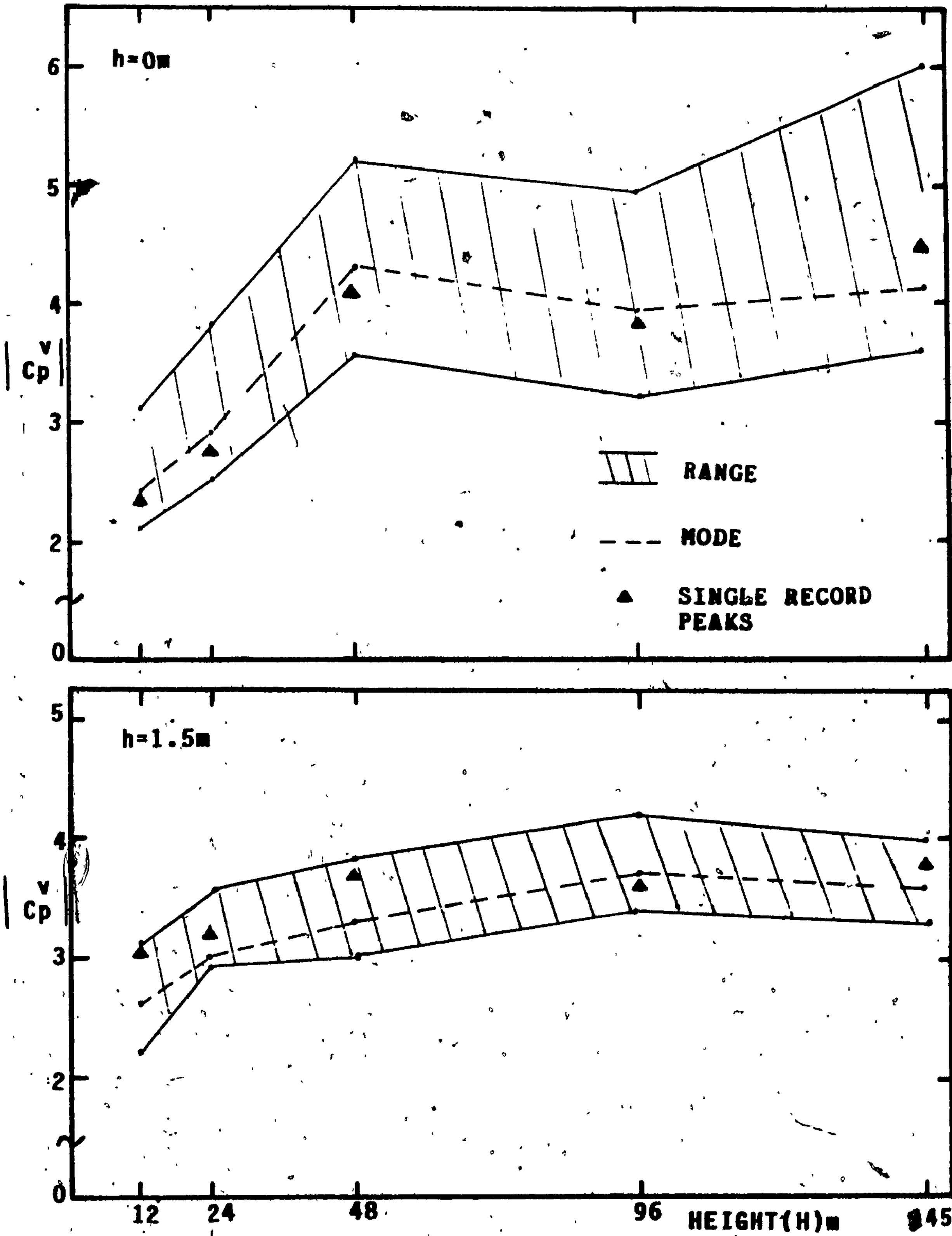


FIG. 5.3 SINGLE RECORD PEAKS AND EXTREME VALUE DISTRIBUTION DATA

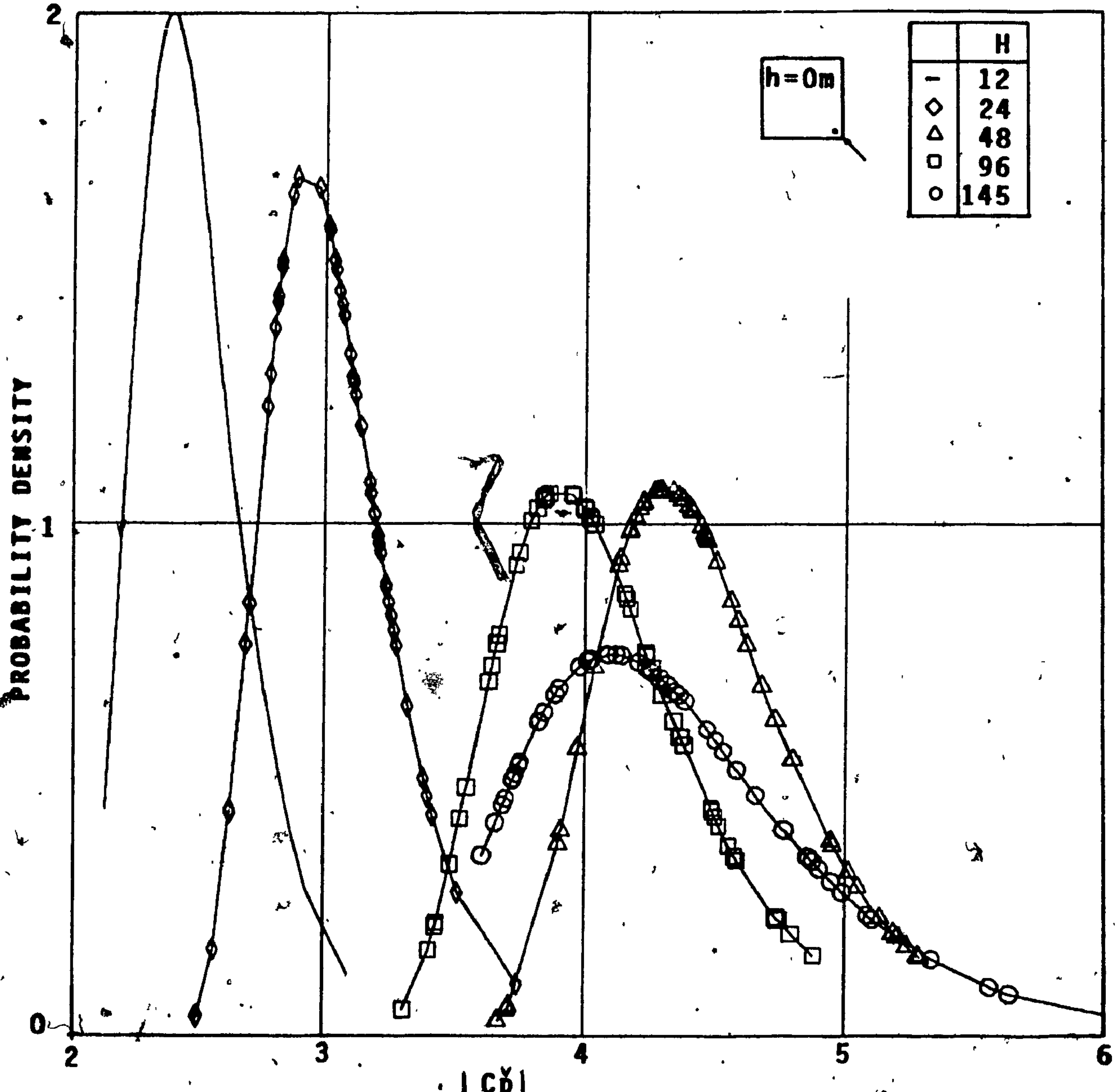


FIG. 5.4 PROBABILITY DENSITY FUNCTIONS FOR A FLAT ROOF CORNER WITHOUT PARAPET

loadings. Figure 5.5 shows PDF data for buildings with a 0.75 m parapet whereas Fig 5.6 presents the influence of a 1.5 m parapet. It is interesting to note that suction peaks on tall building corners shift to smaller values in the presence of parapets. In the cases of 1.5m parapet, the tallest building has the lowest suction peaks, whereas roof corner suctions for the lowest building have increased. The possible error by selecting a single - record peak suction value is thus expected to be smaller in the case of roof with rather than without parapets.

The same type of approach was followed for an edge pressure tap. Pressure records were collected for the different building configurations tested. PDF and EVD data in the same format are presented in Figures 5.7 and 5.8 respectively. The data confirm that for all buildings, the parapet reduces the pressure coefficients (comparison of mode values). In this case however, parapets do not appear to affect the effective width of PDF functions and some overlapping between configurations "with" and "without" parapets dose occur. This may explain some inconsistencies noticed on the behaviour of some buildings regarding the effect of parapets on wind loads of roof edges - see Fig. 4.16.

The discussion sheds some light into the randomness involved in the peak pressure measurement and provides an

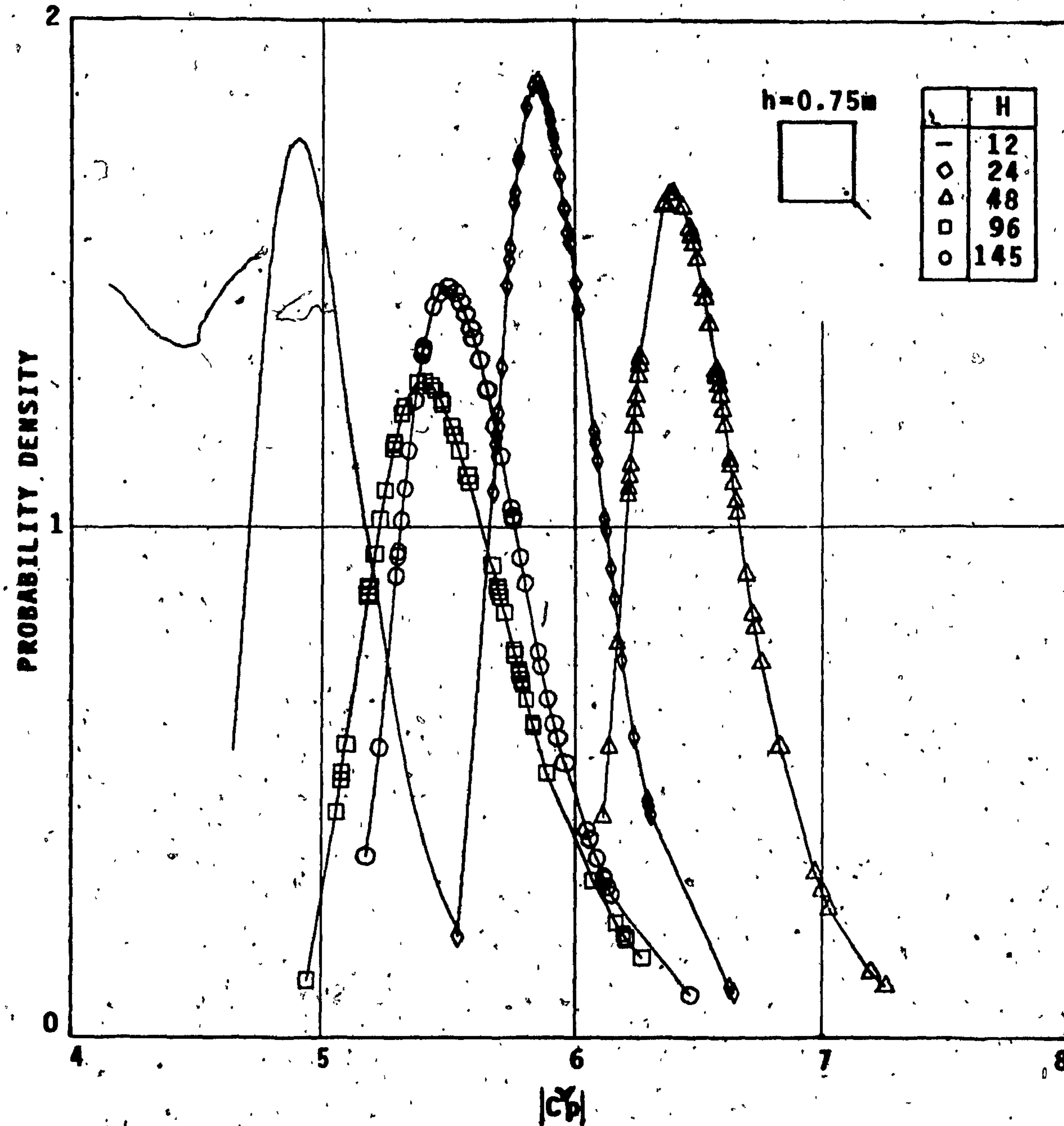


FIG. 5.5 PROBABILITY DENSITY FUNCTIONS FOR A FLAT ROOF CORNER WITH 0.75m PARAPET

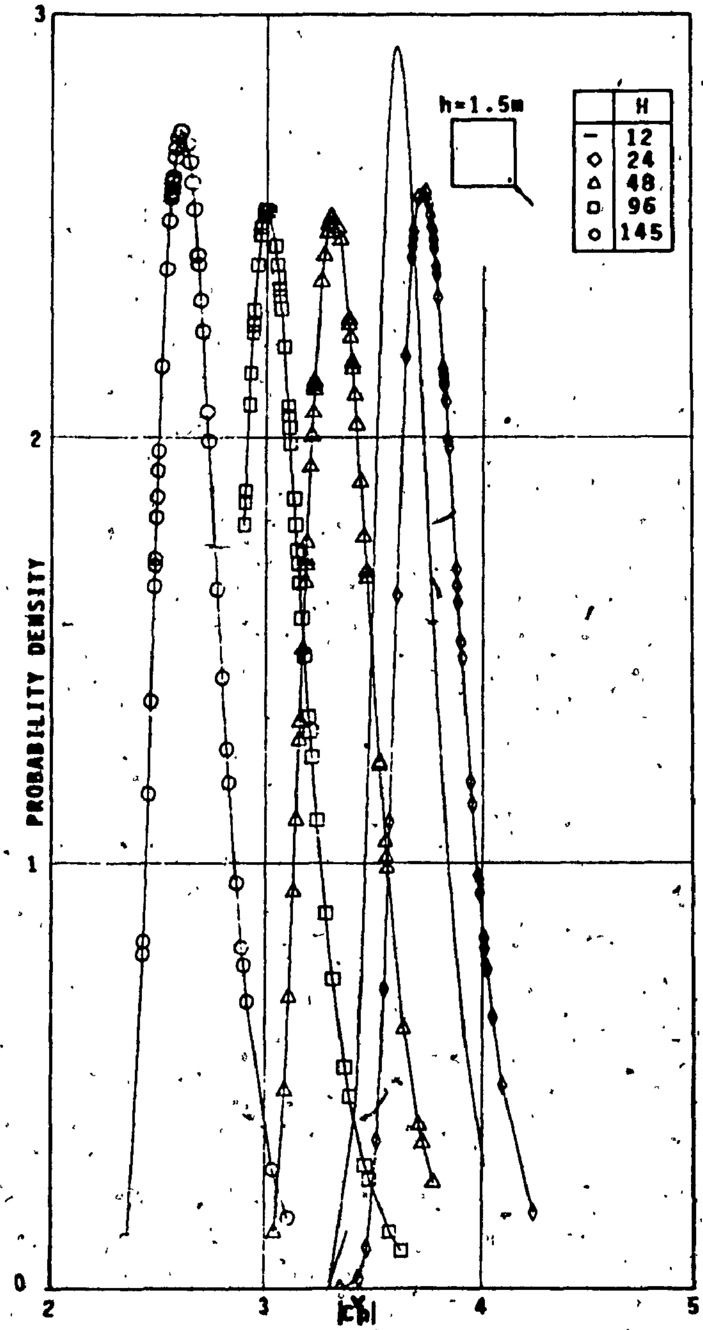


FIG. 5.6 PROBABILITY DENSITY FUNCTIONS FOR A FLAT ROOF CORNER WITH 1.5 m PARAPET

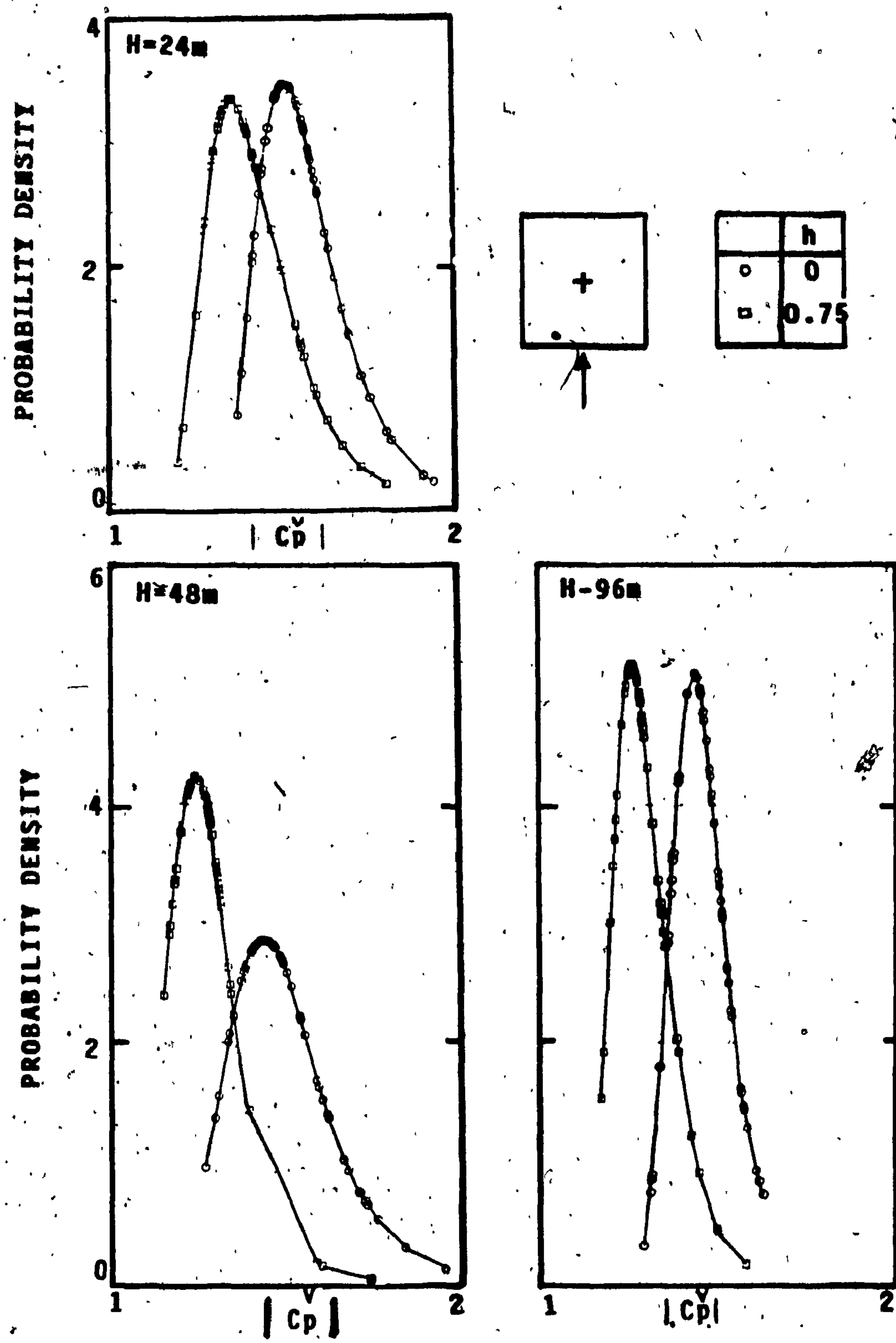


FIG. 5.7 PROBABILITY DENSITY FUNCTIONS FOR FLAT ROOF EDGES WITH AND WITHOUT PARAPETS

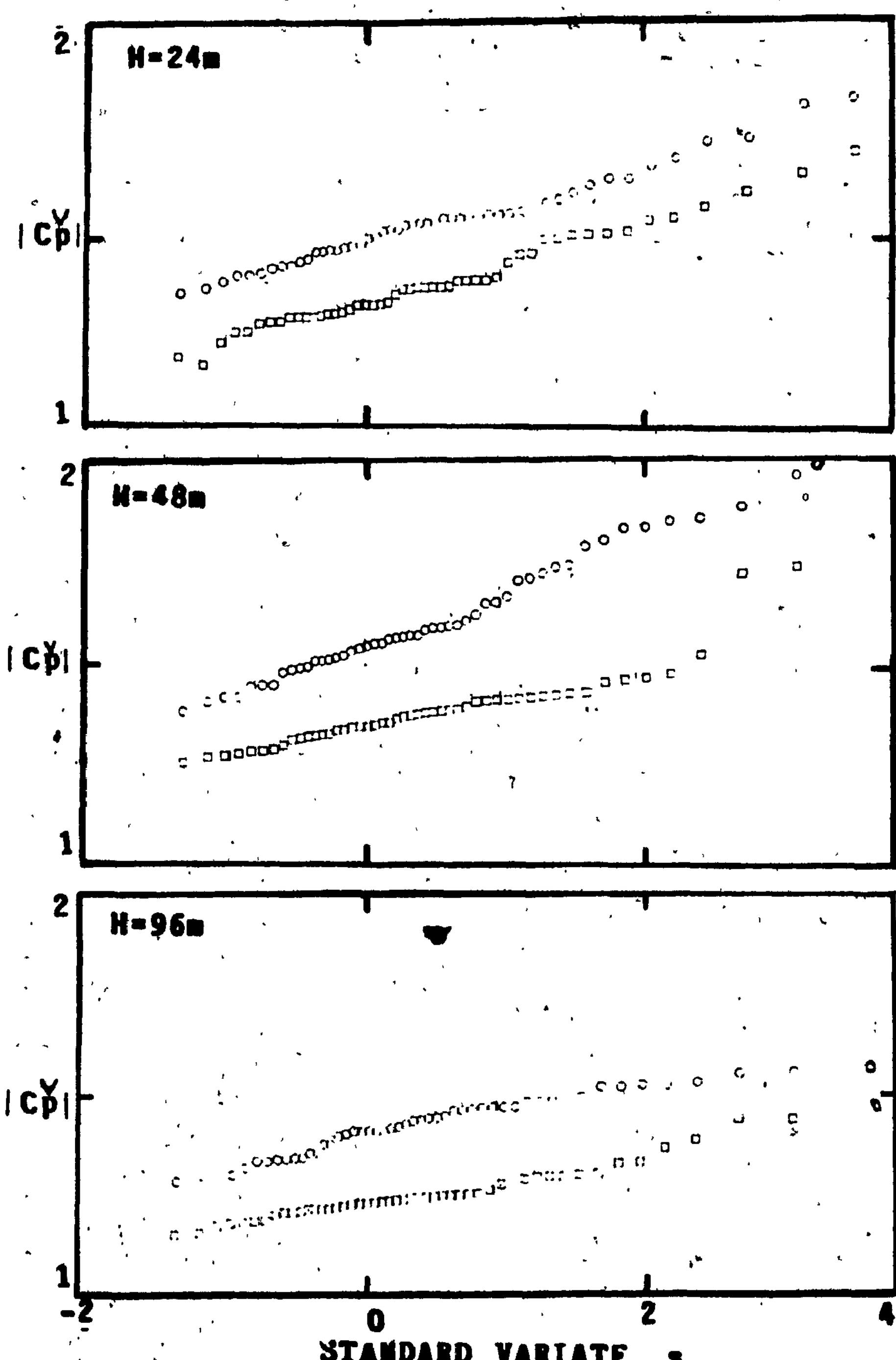


FIG. 5.8 EXTREME VALUE DISTRIBUTIONS FOR FLAT ROOF EDGES WITH AND WITHOUT PARAPETS

idea about the possible errors they may occur in the estimation of peak pressures. The comparison of the single - record peaks and EVD peaks is generally, encouraginig. Furthermore, the role of parapet in reducing the possibility of error for critical design loads has also been identified.

CHAPTER 6

APPLICATION FOR STANDARDS AND CODES OF PRACTICE

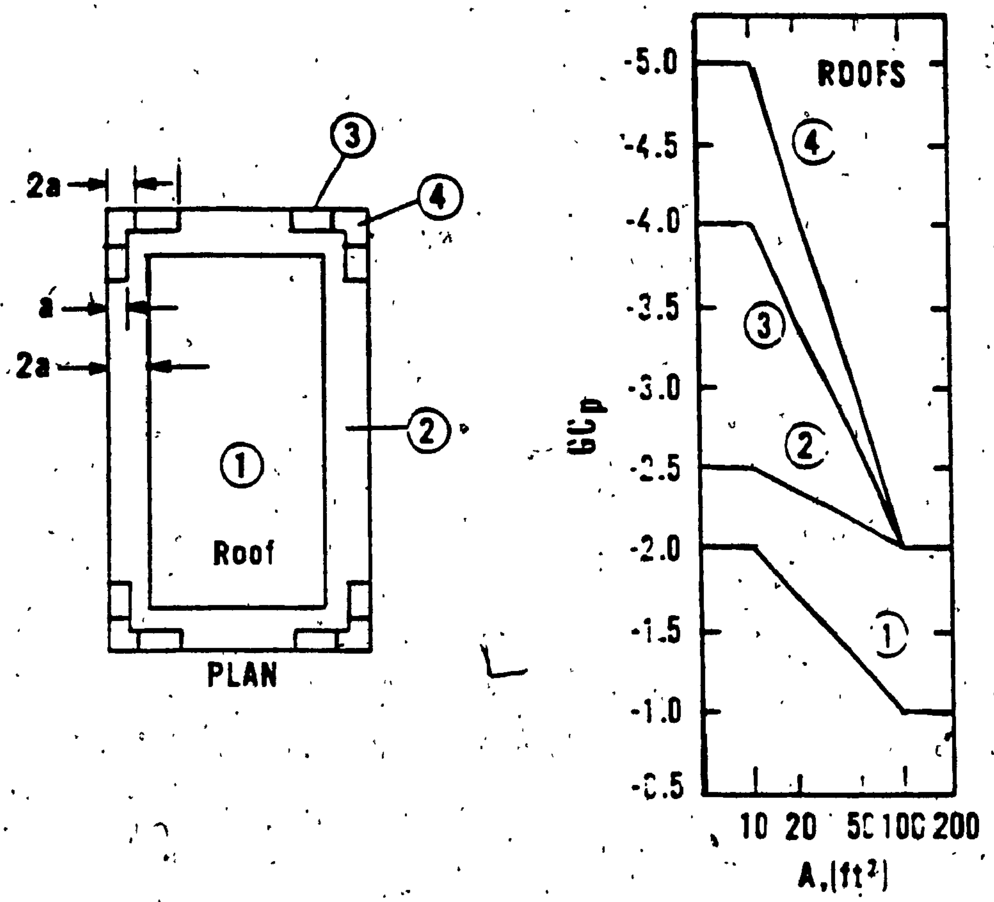
" Code loads are conventional loads."

....M.G.Salvado

Based on the experimental data and the analysis of the results some useful suggestion for Wind loading Standards and Codes of Practice can be made. This chapter is divided into two sections. The first section describes the recommendations available in wind standards, whereas the second section suggest how the results of the present study can be implemented in practice.

6.1 CURRENT PROVISIONS OF WIND STANDARDS

As discussed in the chapter 2 the majority of Wind Codes and Standards have no specifications regarding wind loads on roofs with parapets. However, the ANSI Standard (1) provides a recommendation for the design of tall building roofs (H >20m) with parapets as shown in Fig.6.1, reproduced from ANSI. According to ANSI the building roof can be separated as interior region (1), edge region (2)



NOTE:

(1) VERTICAL SCALE DENOTES GCp TO BE USED WITH APPROPRIATE q_z OR q_h

(2) HORIZONTAL SCALE DENOTES TRIBUTARY AREA A, IN SQ. FT.

(3) USE q_h WITH NEGATIVE VALUES OF GCp VALUES OF GCp.

(4) IF A PARAPET IS PROVIDED AROUND THE ROOF PERIMETER ZONES (3) AND (4) MAY BE TREATED AS ZONE (2)

NOTATION:

a : 5% OF MINIMUM WIDTH OR 0.5h, WHICHEVER IS SMALLER
h : MEAN ROOF HEIGHT, IN FEET

FIG.6.1 EXTERNAL PRESSURE COEFFICIENTS, GCp, FOR LOADS ON BUILDING COMPONENTS AND CLADDING FOR BUILDINGS WITH MEAN ROOF HEIGHT h GREATER THAN 60 FEET (1) and corner regions (3 and4). The gust pressure coefficients given in Fig.6.1 must be multiplied by the reference dynamic pressure at roof height which can be derived from the fastest mile wind speed and also by an exposure factor to yield the design wind pressure.

Note (4) in the figure suggests the selection of GCp coefficients corresponding to the edge region (2) instead of the corner region (3 and 4) for roofs having parapet around its perimeter. For example, for a roof corner of area up to 10 sq. feet (up to 1.0 sq. meter) and no parapets the coefficient GCp is -5.0 . If a parapet is provided on the same building, the coefficient GCp can be taken as -2.5 regardless of the parapet height. This suggestion of ANSI is based on the assumption that parapets reduce drastically the suction loads on roof corners. This is in contrast with the results of the present study, which have clearly shown the drastic increase that a low parapet may cause on roof corner loads. Nevertheless, the ANSI provision can be justified based on these grounds:

1) Note (4) was suggested following Leutheusser's study (22) which was carried out in an aeronautical type wind tunnel where the wind velocity is uniform and the natural wind characteristics are not simulated.

2) In Leuthuesser's experimental work parapets less than 1.0 m, for which the roof corner wind loads are increased, have not been considered.

Figure 6.2 represent the provisions made by the European Standard (12). For flat roofs without a parapet the external pressure coefficient can be taken as -5.0 and this value remains unaffected for roofs with low parapets. This provision seems to be more representative for tall building roofs with low parapet but it does not seem to hold for low buildings with low parapets. It is also suggested that pressure coefficient can be reduced further with increase of parapet height regardless of the building height. The sourace study for these provisions is not clear to the author.

At present the National Building Code of Canada (27) has not any specifications for wind loads on roofs with parapets. Some suggestions have been made by Stathopoulos (38) for low building roofs with parapet and they are summerized here:

1) Wall loads should remain unaffected by the presence of parapets.

2) The roof verge local high suctions may be reduced by 30 % in the presence of parapets.

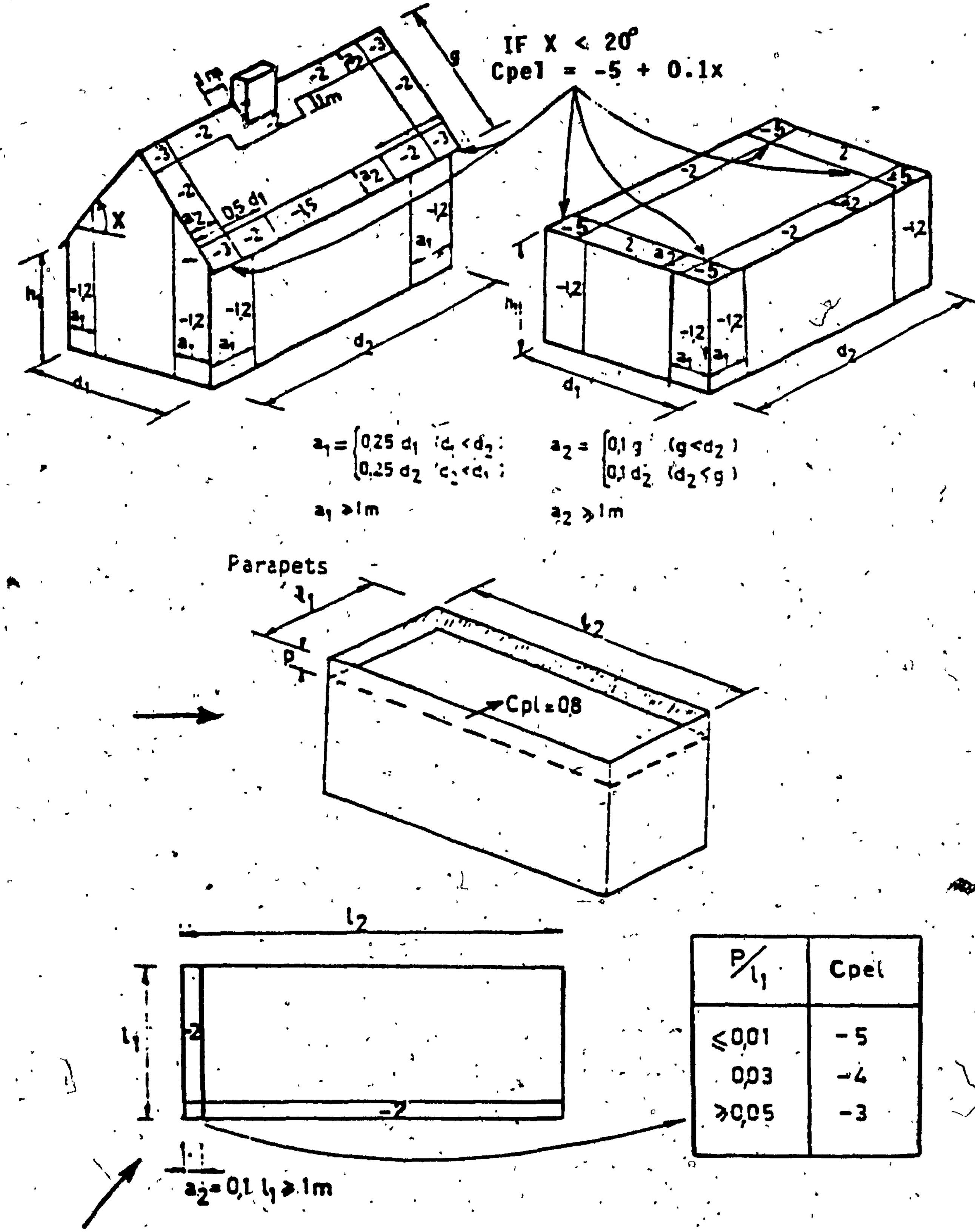


FIG. 6.2 LOCAL EXTERNAL PRESSURE COEFFICIENTS, (12) Cpel

3) The local suctions on the interior roof areas should be increased by 5% for buildings with parapets.

4) No reductions for large tributary areas loads acting on roof corner reggions should be allowed in the presence of parapets.

6.2 RECOMMENDATIONS BASED ON THE RESULTS OF THE PRESENT STUDY

Based on the results of the present study the following recommendations for Wind Standards and Codes of Practice can be made:

I. Building roofs with low parapet (less than 1.0 m)

a) Code or Standard provisions for interior regions of roof without parapet are equally applicable to roofs with parapet.

b) Edge design loads may be reduced by 20 - 30 % depending on the height of the building.

c) Roof corner local suction loads have to be increased around 30 % for tall buildings and 50 % low buildings.

II) Building roofs with high parapet (greater than 1.0m)

a) Code or Standard provisions for interior regions of roofs without parapet are equally applicable to roofs with parapet.

b) Edge design loads can be reduced by 50% for tall buildings and 20 % for low buildings.

c) No larger reductions are permitted on wind loads acting on roof corners of low buildings and a small reduction of 20 % may be allowed for tall buildings.

The suggestions listed above are generally applicable for buildings with low roof angles (0 - 10) having a perimetrical parapet and for wind coming from any direction. Since previous studies (9,40,47) have found that the length of the building has relatively small effect on critical values of roof wind pressures. So the above recommendations may be applicable for buildings having different aspect ratio.

CHAPTER 7

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 roofs with parapets has been carried out. The study was experimental and it was performed at the Building Aerodynamics Laboratory of the Centre for Building Studies.

Different building 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. Furthermore, attempts have been made to understand the behaviour of corner wind loads by using spectral analysis. Extreme Value Distribution analysis has also been used for the quality assurance of the peak pressure coefficients measured in wind tunnel. The assessment of the wind loads has been made under two different terrain conditions (open country - urban).

The experimental results indicate that for all different configurations tested, parapets generally reduce the high suctions on the roof edges and may only slighty affect the loads acting on the interior areas of the roof. Roof corners which suffer the majority of failures are affected differently by a significant increase in both mean and peak suctions for all buildings with low parapets. This increase may be critical if one considers that a parapet about 0.75m high is used in most flat-roof buildings. Spectral measurements on roof corners show that the parapet decreases the high frequency content of the fluctuating pressure for oblique directions.

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 increasing terrain roughness, whereas mean values remain generally the same.

Applying the results in practice reveals that the ANSI Standard (1) specifications for wind loads on buildings with parapets may be inadequate for roof corner areas. Some suggestions for Wind Standards and Building Codes of Practice based on the results of the present study have been made.

More experimental results are required inorder 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 only around some edges or part of the building roofs.

Overall wind loads on flat roofs are reduced due to parapets with the exception of corner areas. Therefore, it is recommended for future research to vent the roof corner suctions with parapets. Slotting the parapets at the corners may be considered as an alternative. Finally, wind loads on parapet surfaces must also be evaluated in order to determine whether parapets are economically justifiable as a means for reduction of wind loads acting on building roofs.

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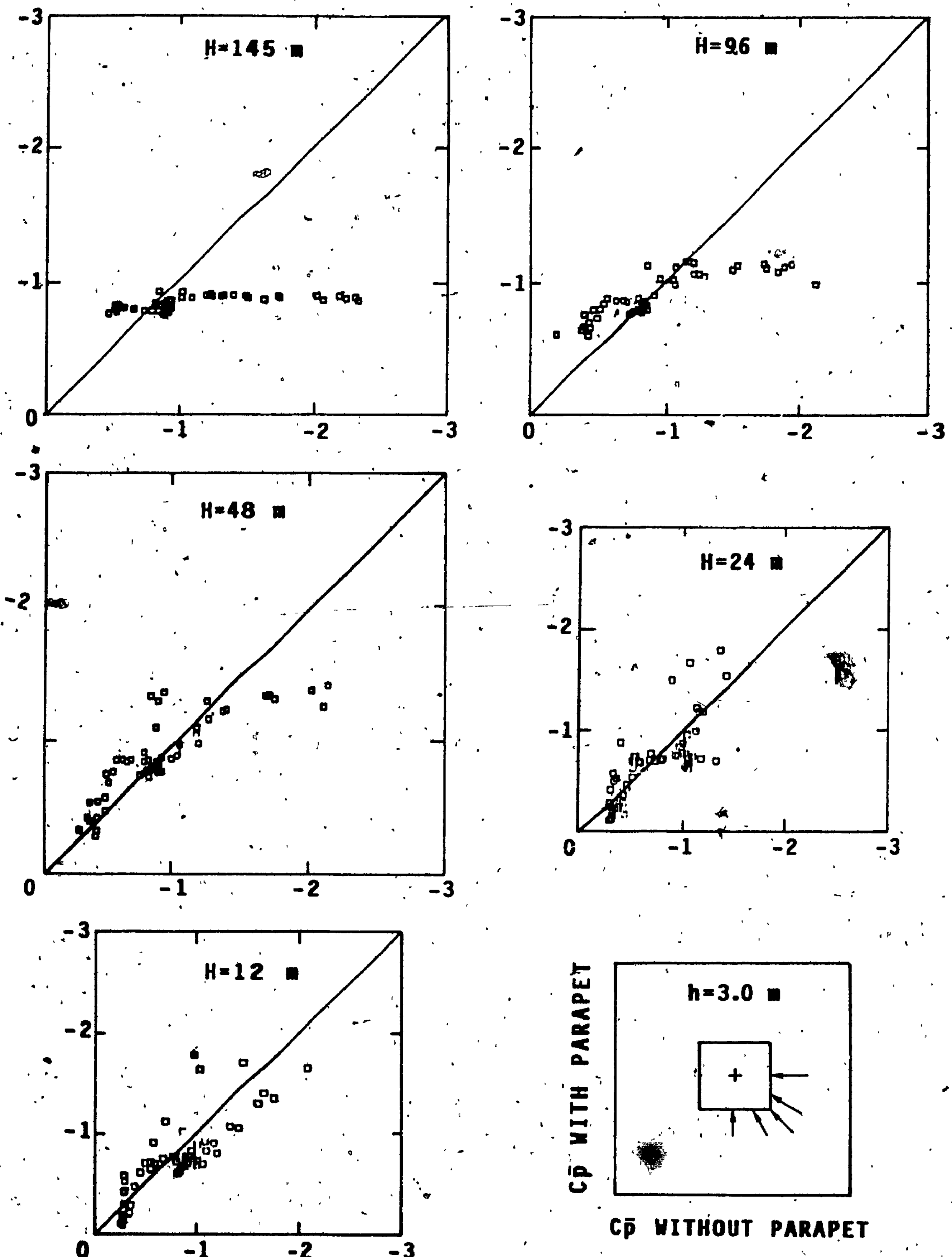
APPENDIX-1: EFFECT OF PARAPETS ON MEAN AND PEAK PRESSURE COEFFICIENTS ACTING ON FLAT ROOFS EXPOSED IN OPEN COUNTRY TERRAIN



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H=48 m
H=24 m
H=12 m
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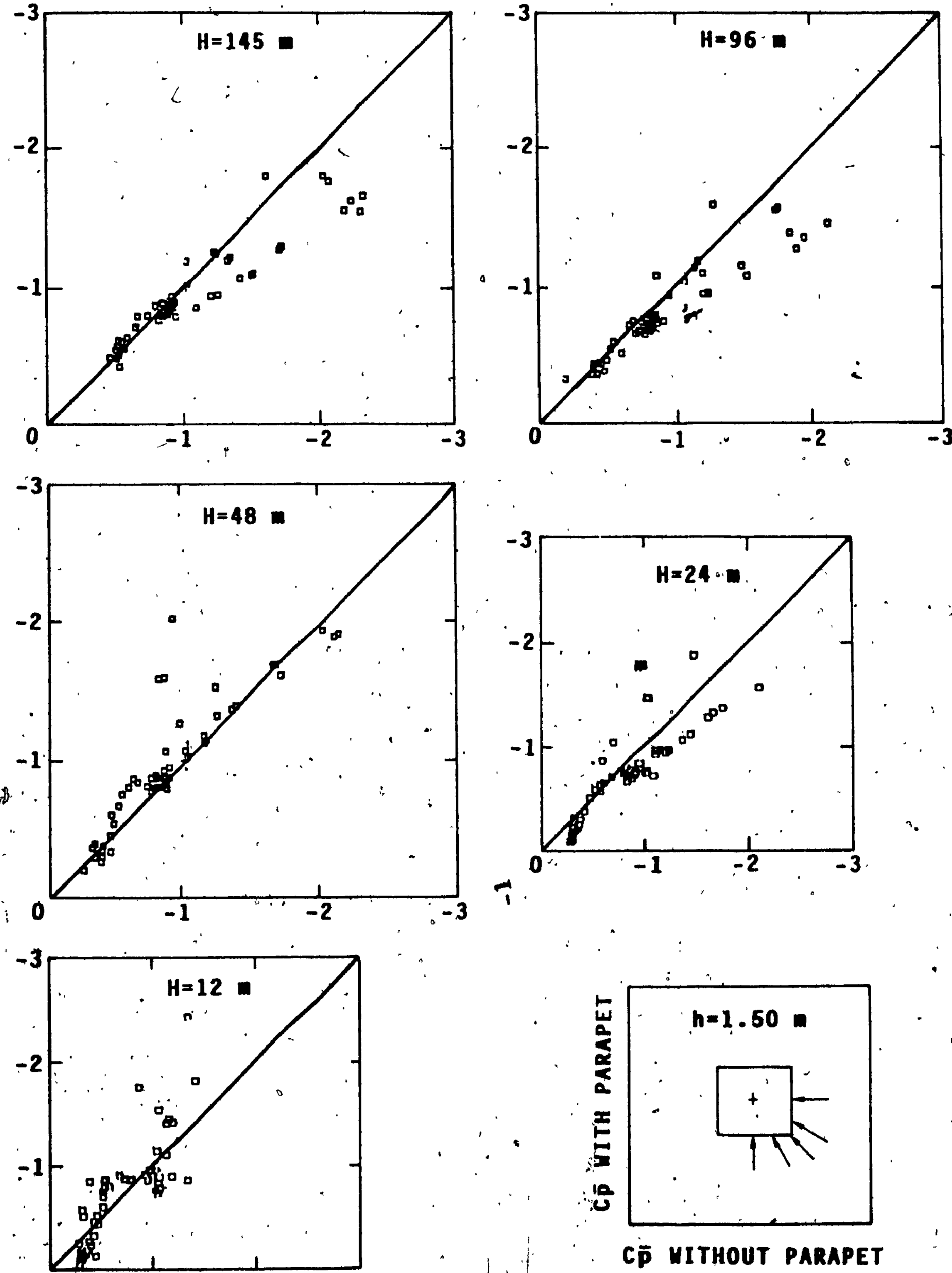
Cp̄ WITH PARAPET
Cp̄ WITHOUT PARAPET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-2
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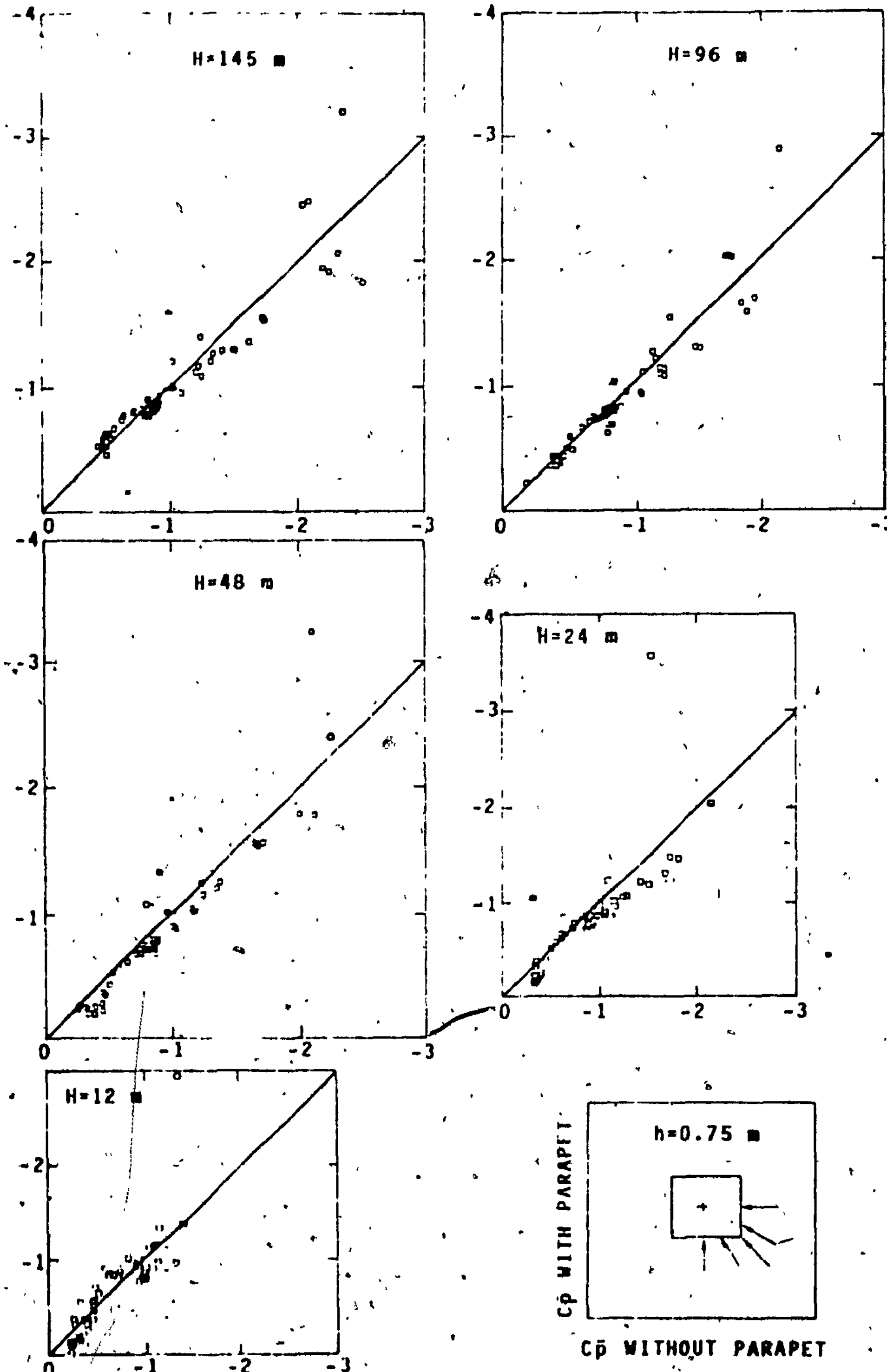
Cp̄ WITH PARAPET
Cp̄ WITHOUT PARAPET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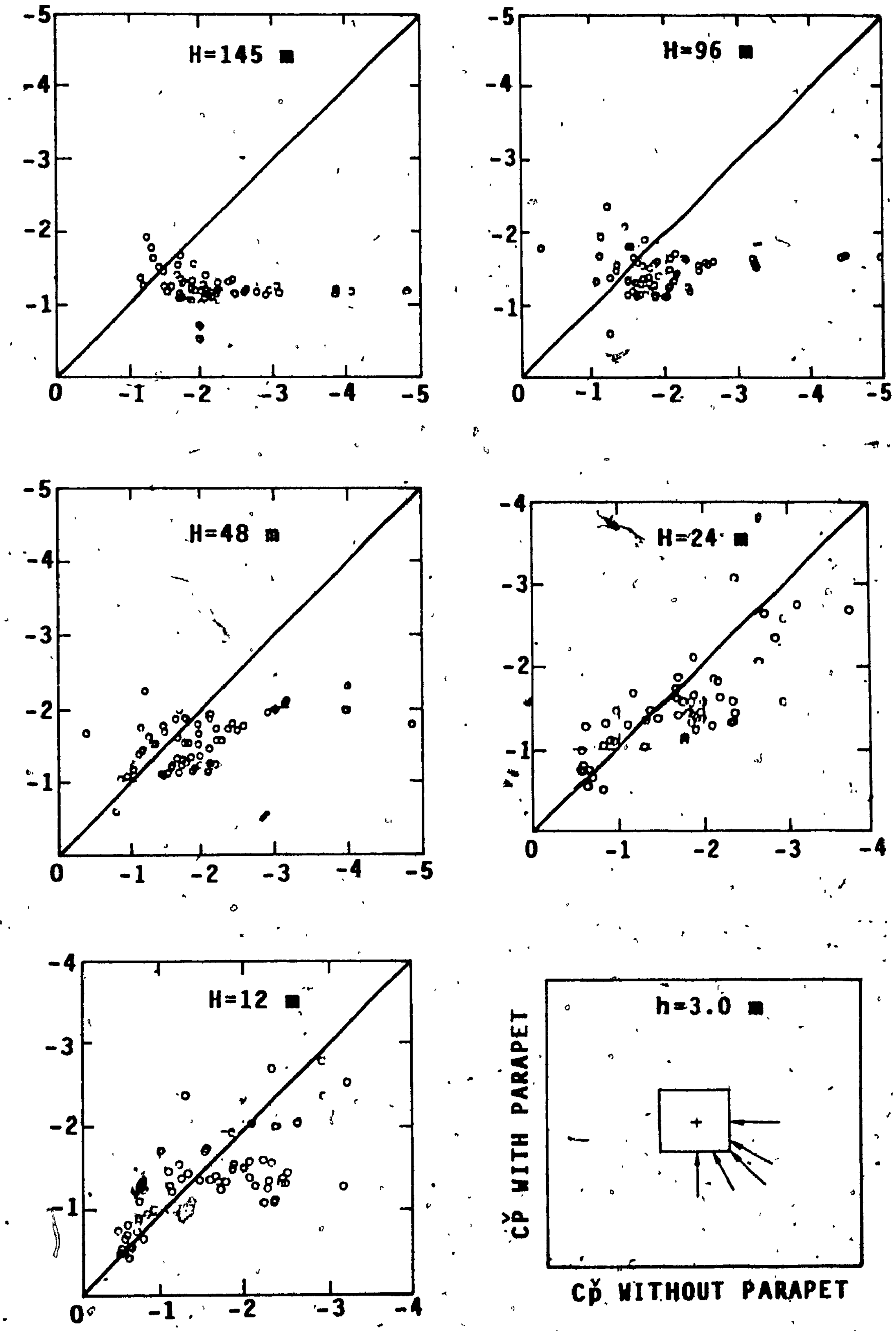
Cp WITH PARAPET
Cp WITHOUT PARAPET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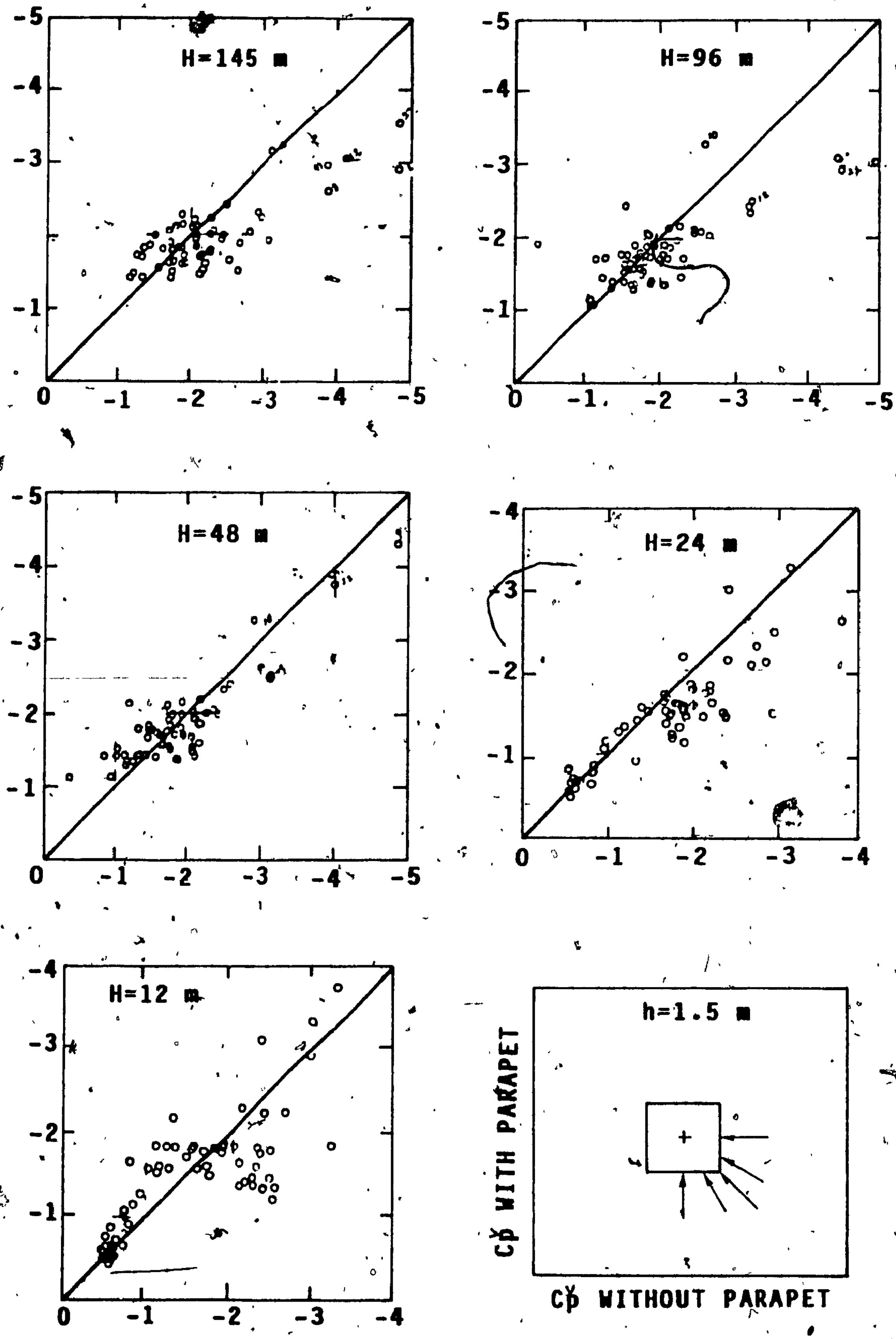
Cp̌ WITH PARAPET
Cp̌ WITHOUT PARAPET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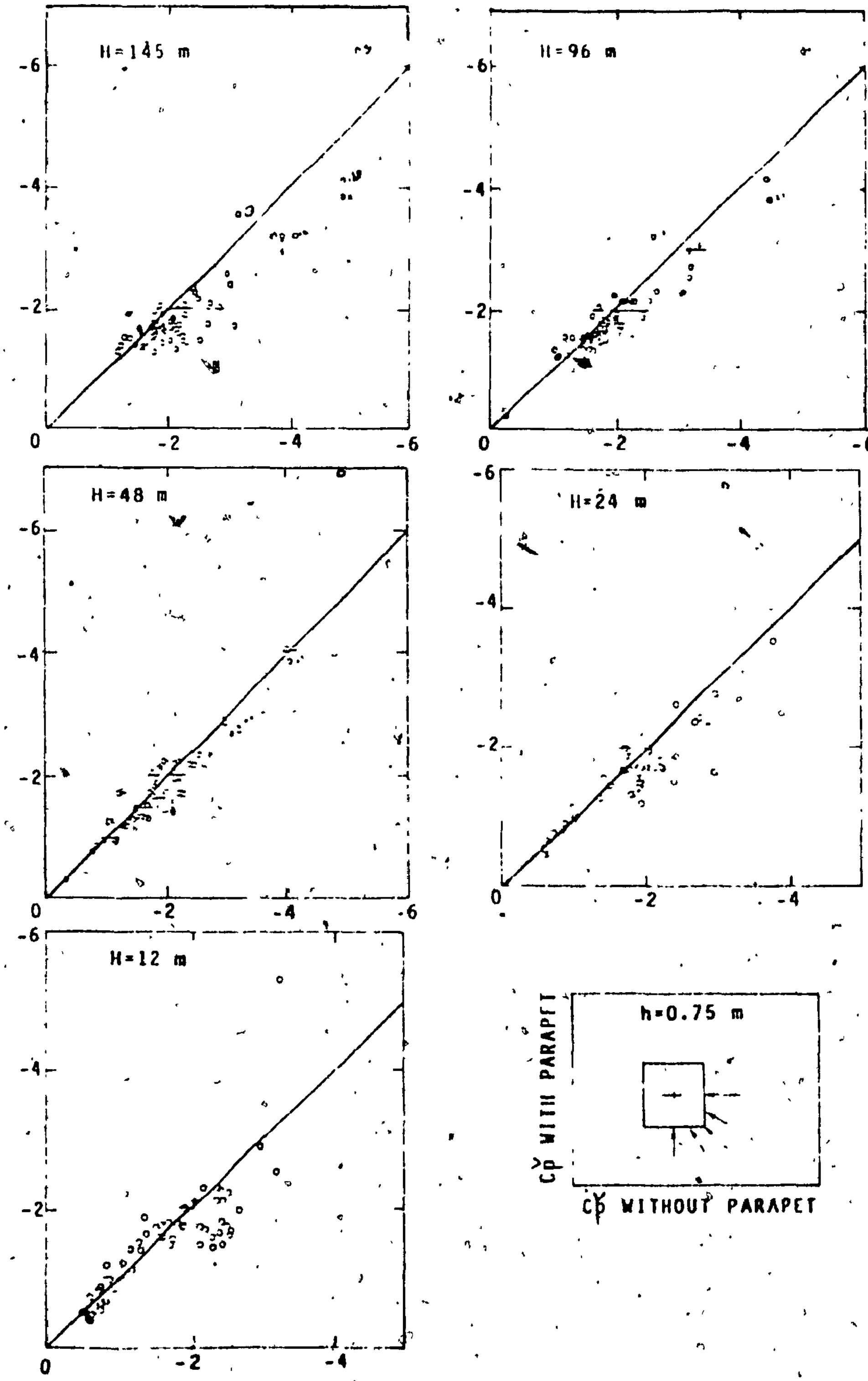
Cp WITH PARAPET
Cp WITHOUT PARAPET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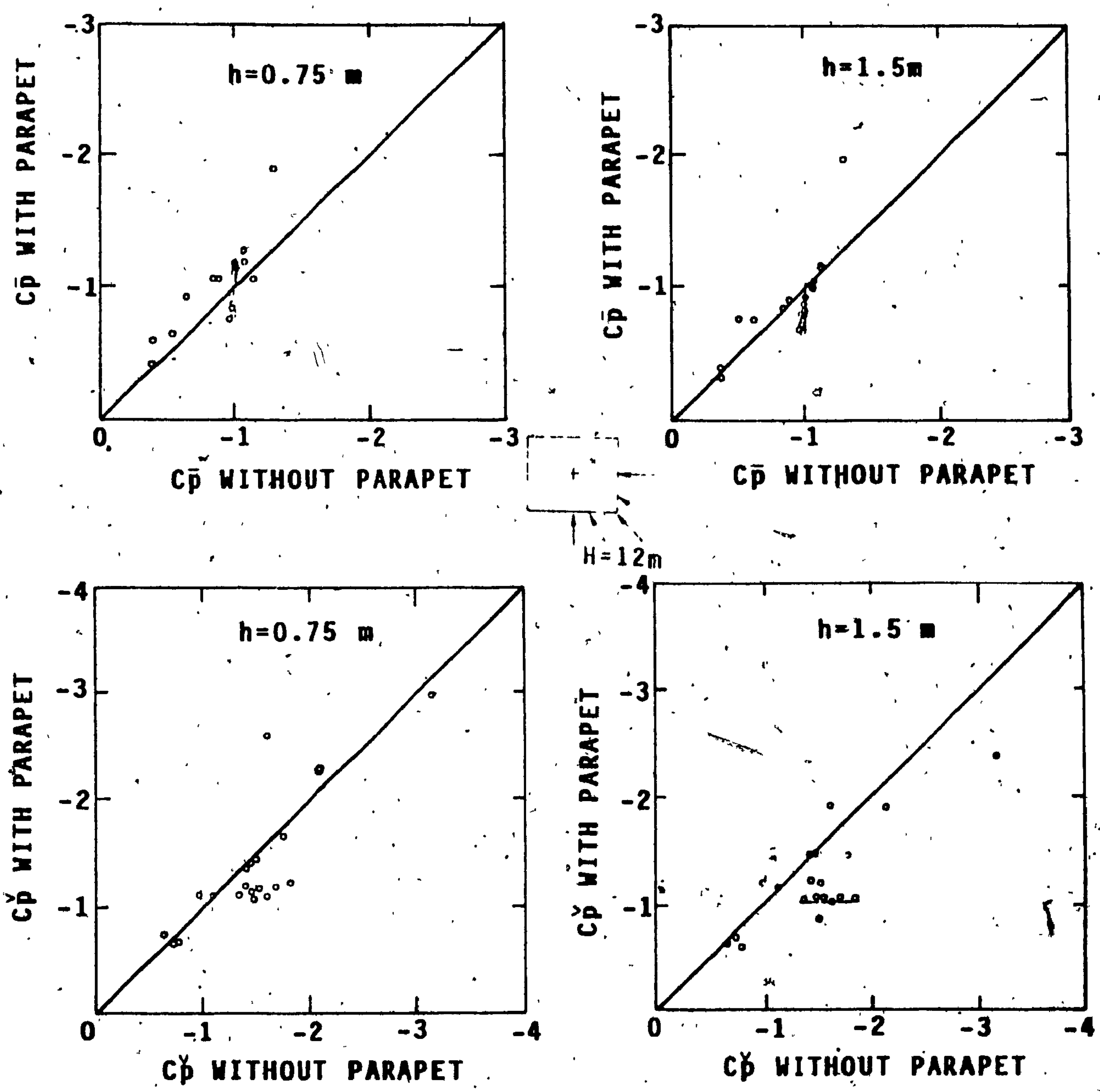
H=24 m
H=12 m
h=0.75 m
Cp WITH PARAPET
Cp WITHOUT PARAPET

APPENDIX-2: EFFECT OF PARAPETS ON MEAN AND PEAK PRESSURE COEFFICIENTS ACTING ON FLAT ROOFS EXPOSED IN URBAN TERRAIN.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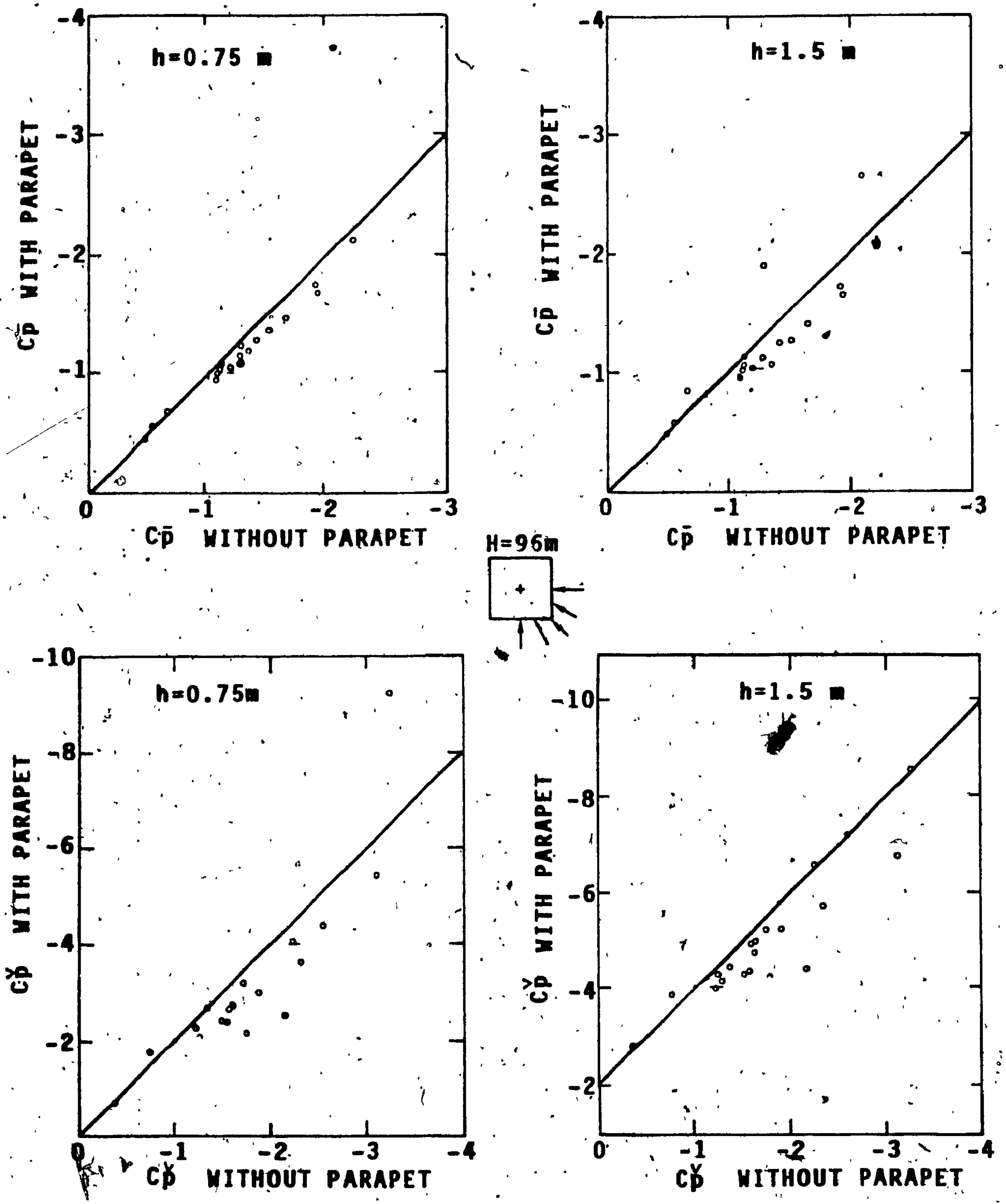
h=1.5m
C$\bar{p}$ WITH PARAPET
C$\bar{p}$ WITHOUT PARAPET
H=12m
h=0.75 m
h=1.5 m
C$\check{p}$ WITH PARAPET
C$\check{p}$ WITHOUT PARAPET
0
-1
-2
-3
-4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Cp̄ WITHOUT PARAPET
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Cp̄ WITHOUT PARAPET
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h=0.75m
Cp̌ WITH PARAPET
Cp̌ WITHOUT PARAPET
h=1.5 m
Cp̌ WITH PARAPET
Cp̌ WITHOUT PARAPET