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THE INTERFERENCE EFFECT OF SURROUNDING ROUGHNESS ON WIND PRESSURES OF RECTANGULAR PRISM

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Abstract: *Systematic experiments were conducted in a wind tunnel in order to find the effect of typical building arrangements on the wind-induced pressures, the primary goal is to better understand and quantify the effect of surrounding blocks on wind pressures of central rectangular prism, especially for those magnified situations of peak pressures which is most important for cladding elements on buildings. The parameters related to rectangular prisms include relative height, area density and arrangement of surrounding roughness. Based on these results, more comprehensive conclusions should be made which will lead to some recommendations for wind standards or building design.*

Keywords: interference effect, rectangular prism, surrounding roughness, wind pressure.

1 INTRODUCTION

Since buildings are seldom isolated, the wind pressures to which they will be subject will be influenced by the proximity of other structures. When a building especially the low-rise building is exposed to winds in the atmospheric boundary layer, the building is actually one of the roughness elements since it has approximately the same height as surrounding roughness. Previous results show that wind loads in a realistic environment do not always follow the basic wind load characteristics of an isolated building because of interference by neighboring roughness. Ho et al. [1] investigated low-rise flat roofed buildings, embedded in a typical North-American industrial area. Surry [2] examined the effect of both surroundings and roof corner geometric modifications on the roof pressures measured on a low-rise building. Kiefer and Plate [3] provided modeling of mean and fluctuation wind loads in different types of build-up areas. Chang and Meroney [4] investigate the effect of surroundings with different separation distances, and compared the results of wind-tunnel measurements with that of numerical simulations.

The relevant Code of Practice gives little guide to the designer which enables designer to assess the wind pressures in a situation where there are unusual wind effects caused by the proximity of surrounded buildings. Due to the complex nature of the problem and the lack of reliable data or analytical procedures for predicting the effects of shielding, very little data are available to the designer by which he may take account of the departures from the figures for wind loads given for single buildings in the relevant Code of Practice. Most of the Codes resource the decision of wind loading for buildings in groups to wind tunnel tests, such as AIJ2004[5] and ASCE/SEI 7-05[6]. A detailed and comprehensive study on interference effects of grouped low-rise buildings was carried out by Holmes and Best [7]. Their results, with those of Hussain and Lee[8], were incorporated in The Australian Standard for Minimum Design Loads on Structures[9] in terms of a shielding multiplier (between 0.7 and 1.0), depending upon the spacing, dimensions and the number of upstream buildings) for the derivation of the gust wind speeds. However, cases involving a few upstream buildings, where wind speeds might actually be increased drastically have yet to receive the attention they deserve by the codes, mainly because of the lack of adequate data on which to base codal guidelines and recommendations. For the flow mechanism of the shelter effect of surrounding buildings, many researchers gave their understandings, Chang and Meroney [4] studied the effect of surroundings with different separation distances on surface pressures on low-rise buildings. They pointed out that the shielding effects depended on the ratio of spacing distance to building Height and the number of upstream buildings. The flow in the street canyons can be classified as skimming flow, wake interference flow, or isolated roughness flow depending on the value of this ratio, which was also proposed by Hussain and Lee [8] but with different spacing ratio range.

Compared to those on a smaller group limited to two or three buildings which aimed to give an insight into physical principles, there have been very few studies on a large group of buildings probably due to the difficulties caused by the many parameters involved such as surrounding building size, shape, arrangement pattern and spacing density etc. A majority of studies in this area have been done to investigate wind pressure characteristics from the point of view of natural ventilation [10]. The study of interference effects on a large group of buildings indeed was a daunting task, given the complexity of building arrangements and the complex nature of wind: nevertheless, the findings contributed to our knowledge and understanding of the interference mechanism due to the grouping effects of buildings. Furthermore, gradually this topic forms a class of its own based on some common characteristics. All studies highlight the fact that increasing the number of surrounding obstructions generally reduces the wind loads on a building because increasing the number of nearby structures of significant size would result in less severe wind downstream, leading to net shielding effect. Sheltering effect offers protection on inner buildings in the row at all wind angles. However, it should be noted that such kind of sheltering effects not exist in all cases, the probable magnify effect of extreme wind pressure on the building surfaces will be the focus of this paper.

The results presented here are those of a project undertaken to investigate the interference effects of different groups of surrounded buildings on the wind pressures of central building. Systematic experiments were conducted in a wind tunnel in order to find the effect of typical surrounding building arrangements on the wind-induced pressures, the primary goal is to better understand and quantify the effect of surrounding buildings on wind pressures of rectangular prism. The parameters related include relative height of target prism and surrounding roughness, area density and arrangement of surrounding roughness. The portion of the study reported here focuses on changes in the cladding pressures, that is, on changes of extreme wind pressures. Based on these results, more comprehensive conclusions should be made which will lead to some recommendations for wind standards or building design.

2 WIND TUNNEL TEST

Pressure measurement wind tunnel tests on low-rise buildings were executed in the Boundary Layer Wind Tunnel, in the Tokyo Polytechnic University, Japan. The length scale was set at 1/100□ the velocity scale was assumed at 1/3. The suburban terrain corresponding to terrain category III in AIJ (2004) was chosen as the tested wind field. The wind velocity profile and turbulence intensity profile of the simulated wind field measured in the center of turnable without models are shown in Fig. (1) which is the preformed boundary layer condition for the following studies.

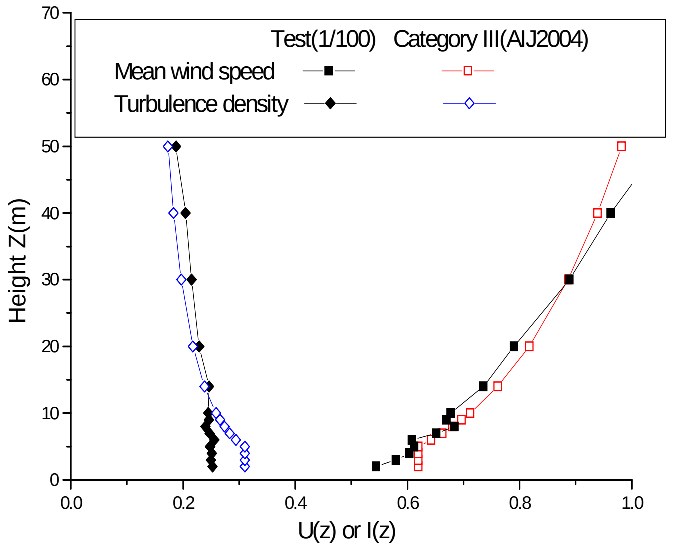


Figure 1: The 1/100 simulated suburban wind field

There are two kinds of models for each type of models. One is the sensor model for the measurement of wind pressure, and the other is the dummy model to make the alignments of the models. The former is made of acrylic plastic, and the latter is wooden model. Only one model of the former is used in each layout.

The rectangular prism models for test have same plan size of 24cm length and 16cm width, and three model heights (*H*), 6cm, 12cm and 18cm. In wind tunnel, a large number of 'dummy' models of similar dimensions were constructed to represent surrounding buildings, and area density C_A was defined as,

$$C_A = \frac{area\ occupied\ by\ buildings}{area\ of\ \ site} = \frac{bd}{BD} \tag{1}$$

where, b and d are the breadth and depth of the center building. B and D are the average distances between corresponding points on adjacent buildings in two coordinate directions, as shown in Fig. (2). The target model is set at the center of a turnable of 200cm, surrounded models are arranged in 3 kinds of orders (i.e. regular, staggered, random), as shown in Fig. (3), with 8 different area density C_A (0.1, 0.15, 0.20, 0.25, 0.30, 0.40, 0.50 0.60), and the heights of surrounding models (H_s) are also varied in 6, 12, 18cm. Each of the experimental models is set on the turntable in isolation settings, that is, without surrounding models ($C_{A=}$ 0.0), which are called isolation test cases.

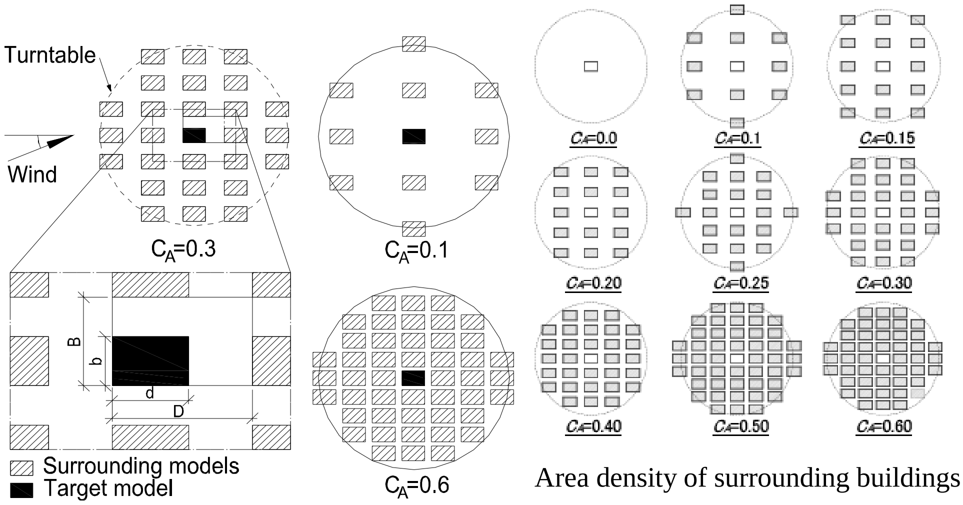


Figure 2: Definition of C_A

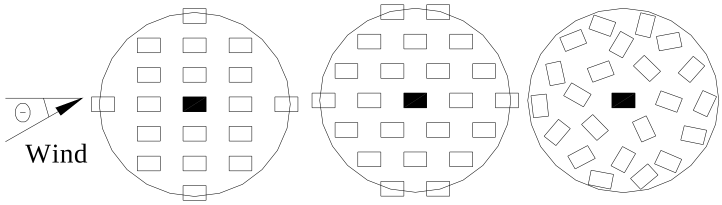


Figure 3: Arrangement Order of surrounding buildings (C_A=0.25)

In this test, the sampling frequency was 781.25Hz and the sampling period was 18 seconds for each sample, corresponding to 23.4Hz and 10 minutes in full scale. The test data were then low-pass filtered at 300Hz. Each test case was sampled 10 times and the statistical values of the wind pressure coefficients shown in this paper are the average of the statistical value of these ten samples. The transfer function of the tube system was identified according to sinusoidal signals input and its corresponding output. The effect of the tube system was eliminated by dividing the transfer function from the power spectra of the measured raw test series.

The wind pressure coefficients were expressed in the form of a non-dimensional pressure coefficient, defined as follows:

$$C_{p\_ori}(i,t) = p(i,t) / p_H \tag{1}$$

where $C_{p\_ori}(i,t)$ is original wind pressure coefficients at measured tap i at time t; $p(i,t)$ is measured wind pressure at tap i at time t; p_H is the reference wind pressure of the approaching wind velocity at the average roof height, $0.5\rho V_H^2$, V_H corresponds to the mean wind speed in preformed boundary layer at the reference height (average height of the roofs). For the present test program, the reference velocity remained essentially constant so that the load changes were directly related to the changes in C_p.

In order to make the wind pressure coefficients correspond to some duration, the time series of wind pressure coefficients were moving averaged as:

$$C_p(i,t) = \overline{C_{p\_ori}(i, t-\Delta t/2 \sim t+\Delta t/2)} \quad (2)$$

where Δt is the duration of the wind pressure coefficients. In this paper, the time series data were moving averaged every 0.0064s, corresponding to 0.2s in full scale. The extreme values were calculated by the Cook & Mayne method, where the extreme distribution of wind pressure coefficients was assumed as a Fisher-Tippett Type 1 (FT1) distribution, the mode and dispersion of the Fisher-Tippett Type 1 are calculated by the Best Linear Unbiased Estimators (BLUE).

The test results of the isolation test cases are referred to as the standard values. In order to quantify the effect of surrounding buildings to the wind pressures of target building, the interference factor, C_I, which represents the change of statistical pressure coefficients caused, is expressed as:

$$C_I = C_{p,sur} / C_{p,iso} \quad (3)$$

where, $C_{p,sur}$ and $C_{p,iso}$ are the local extreme pressure coefficients over all wind directions measured under the experimental model surrounded by neighboring blocks and under the isolated test case, respectively. Furthermore, the maximum values of C_I over area for building surface zones defined by AIJ2004 shown in Fig. (4) are calculated as well, among which the surface Roof, Wall-1 and Wall-2 is denoted for the positive extreme cases.

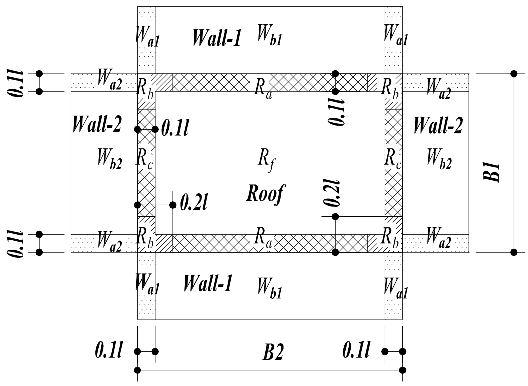
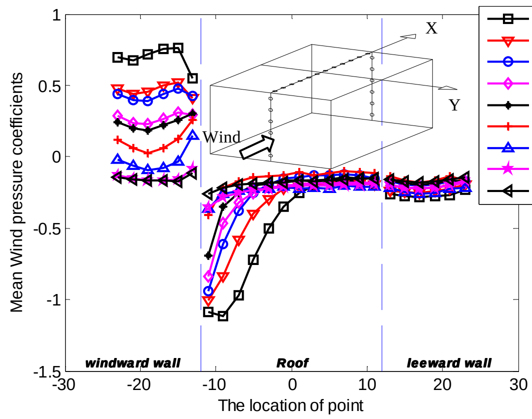


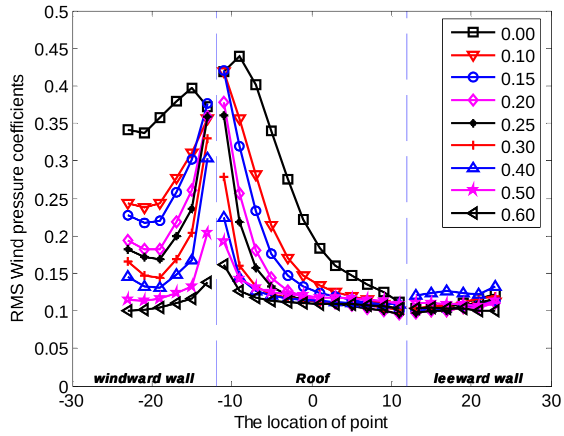
Figure 4: Surface zone definition

3 RESULTS AND DISCUSSION

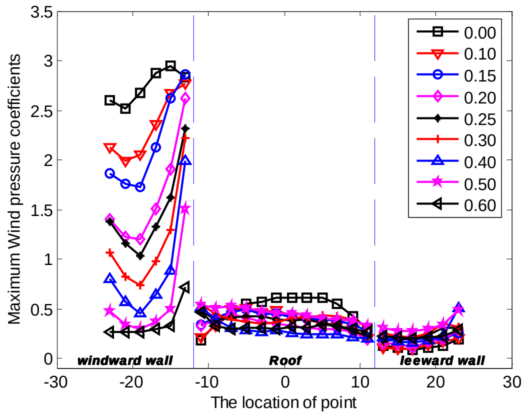
3.1 The effect of area density of surrounding blocks

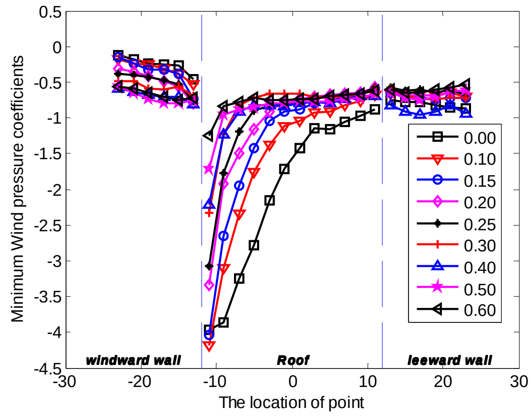
High suction pressures over the prism surface are significantly reduced for a rectangular prism surrounded by other blocks compared to the isolated case in the same approach flow, in terms of the peak, mean or root mean square (RMS) C_p shown in Fig. (5) for detailed C_p comparisons on a single bluff-body block and all surrounding cases depending on the different C_A, where 0.0 means isolated case. All four statistical interpretations of pressure variation are significantly reduced by the presence of surrounding roughness.





(a) Mean wind pressure (b) RMS wind pressure

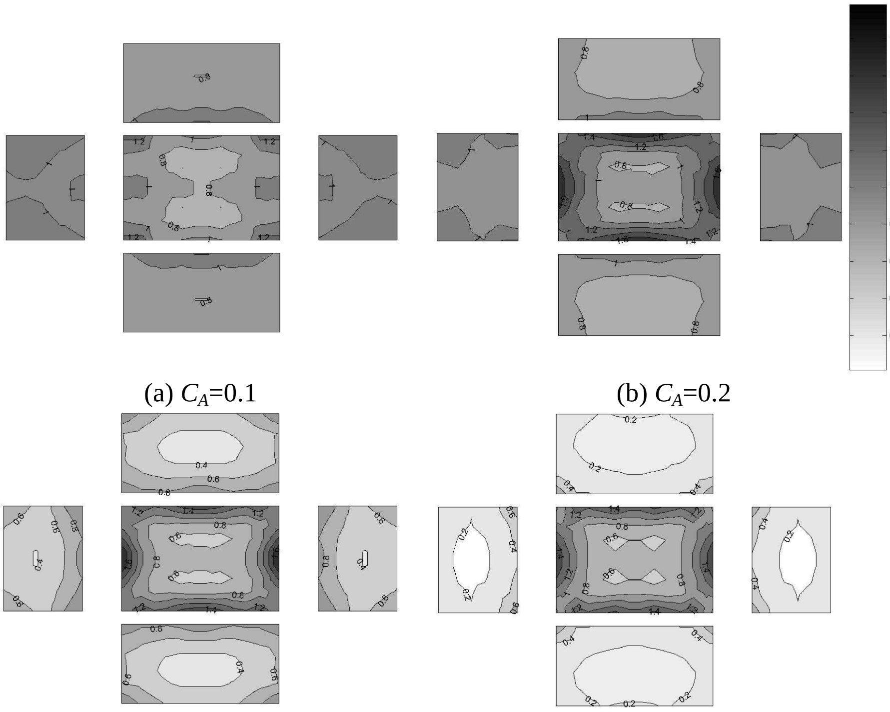




(c) Maximum wind pressure (d) Minimum wind pressure

Figure 5: Pressure coefficients (peak, mean and RMS) on the centerline of building under different C_A at the azimuth of 0, H=12cm, H_S=12cm, in regular arrange order

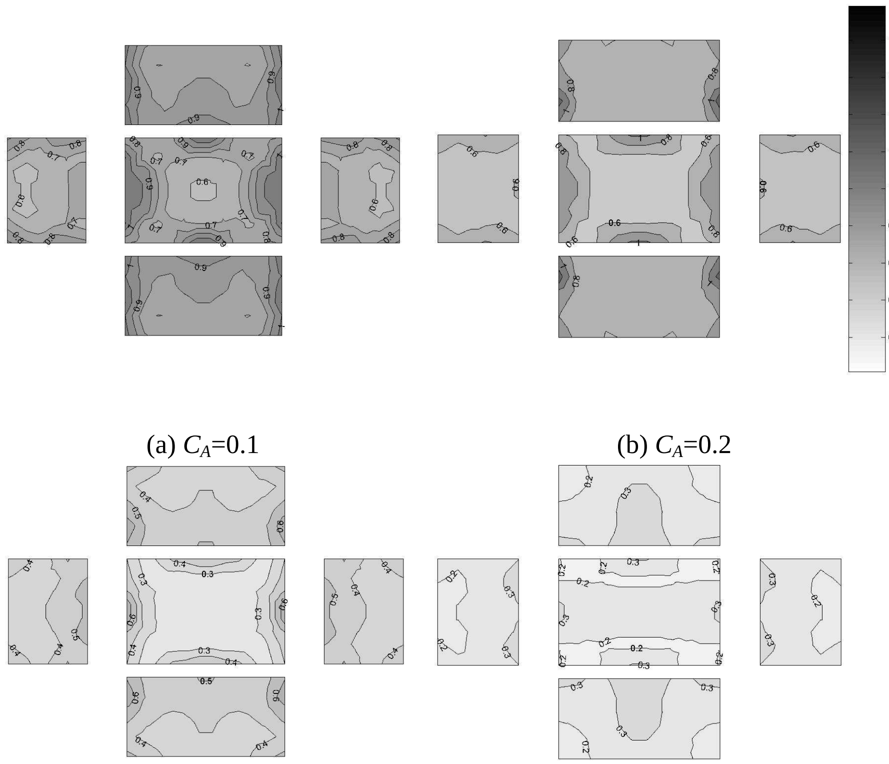
With the decrease of area density, the separation distance between the group increases, the vortices from upstream body can get enough time and space to become well organized before they hit the downstream block, thus the dynamic wind pressures increase as shown from the Fig. (5). On the contrary, for high area density situation, the separation distance becomes smaller, the downstream block interferes with the vortex shedding and disrupts its frequency, thus the vortex shedding mechanism doesn't work and results in small dynamic wind pressures. It should be worthy to note that the fluctuating wind pressure of leeward surface may altered by the wake induced by the downstream block in case of a close proximity, thus resulting in high dynamic wind pressures on it, for example the case of area density of 0.4 for leeward wall in Fig.5. Compare with the isolated case, the extreme wind pressures will be magnified, especially for the positive extreme wind pressures as shown in Fig. (6) for areas along edges of top surface. For negative extreme wind pressures, shielding effect is obvious in all cases.



(a) C_A=0.1 (b) C_A=0.2

(c) C_A=0.4 (d) C_A=0.6

Figure 6: Contour of interference factor for positive peak wind pressures under different C_A (H=12cm, H_S=12cm, in regular arrange order)

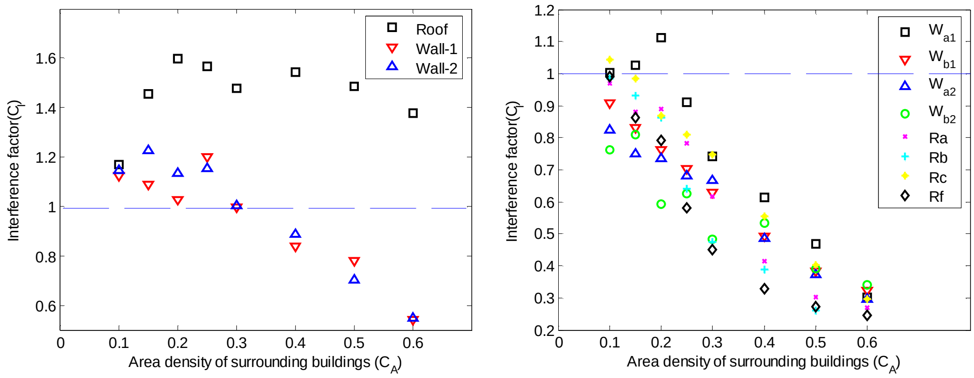


(a) C_A=0.1 (b) C_A=0.2

(c) C_A=0.4 (d) C_A=0.6

Figure 7: Contour of interference factor for negative peak wind pressures under different C_A (H=12cm, H_S=12cm, in regular arrange order)

As the density of surrounding blocks increases, the zoned peak negative wind pressure coefficients on most of the zones decreases, especially for the average peak negative wind pressure coefficients in regular order, as shown in Fig.(8). At the case of relative height ratio of H_S/H=1, with the increase of area density, the interference factors C_I of peak positive wind pressure coefficients of roof are all bigger than 1.0, the magnified value increases gradually until 60% with the increase of the density of surrounding buildings in sparse density cases (C_A <0.2), and then turn to stable of 50% for dense arrangement. For negative extreme wind pressure, there are significant decrease with the increase of C_A and only in sparse density cases (C_A <0.2) the negative extreme wind pressures in the corner of wall surface are bigger than isolated case.

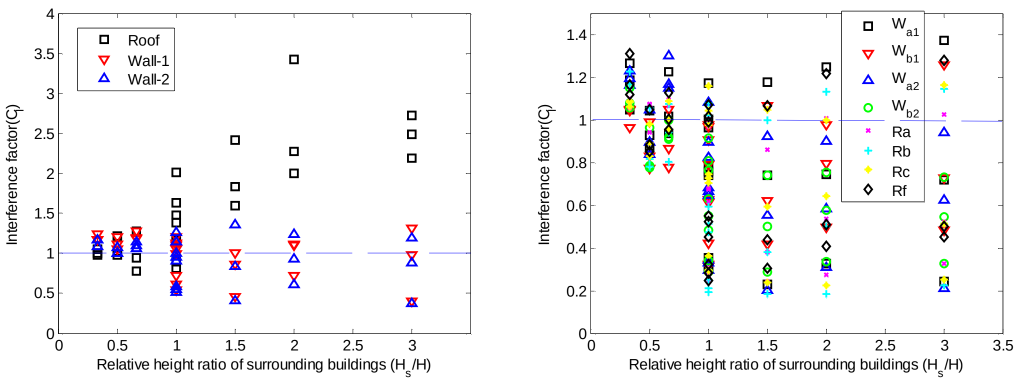


(a) Maximum (b) Minimum

Figure 8: Interference factors for peak wind pressures under different area density cases, H=12cm, H_S=12cm

3.2 The effect of relative height ratio of surrounding buildings to target building

Depending on the relative height ratio (the ratio of height of surrounding buildings to that of target building, H_s/H), there is significant increase of peak positive wind pressure coefficients with the relative ratio on roof areas in regular order, as shown in Fig.(9), and the biggest value for interference factor C_I can reach over 2 times of that of isolated case when the surrounding building is higher than that of the central prism (H_S/H>1.0) which definitely should be paid attention to. For the wall surfaces, the magnified effect is not significant but also can't be neglected totally. It should be noted that the peak negative wind pressure coefficients under lower relative height ratio (H_S/H<1.0) are usually higher than that of bigger relative height ratios (H_S/H>1.0) for most zones.

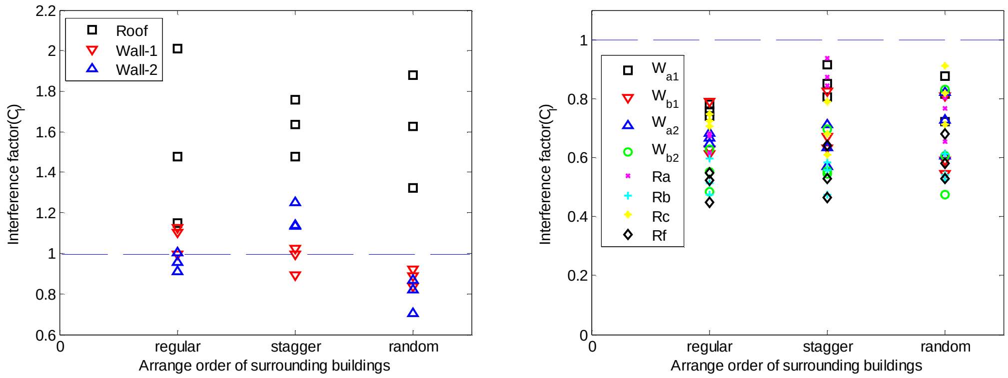


(a) Maximum (b) Minimum

Figure 9: Interference factors for peak wind pressures with different relative height ratio, C_A=0.1, 0.3, 0.6

3.3 The effect of arrange order of surrounding buildings

In particular, the present study would like to detail the relationship between arrangement (e.g. regular, staggered, or random) and the level of interference which results. However, as shown in Fig. (10) due to the scatter of the results, it would be difficult to lead to some clear conclusions, which also indicate that the effect of area density and relation height ratio are much sensitive than the effect of arrangement of surrounding buildings, therefore the different arrange orders become secondary in comparison.



(a) Maximum (b) Minimum

Figure 10: Interference factors for peak wind pressures under different arrangement order, $H/H_S = 1$, $C_A = 0.3$

4 CONCLUSIONS

Shelter effects produced by the surrounding buildings on the central rectangular prism were found to be significant, such that flow patterns are displaced and mean and peak induced loads are significantly different from the isolated building base case. It is expected that shielding effects depend on the area density (C_A) and the relative height ratio (H_s/H). The suction on the building surfaces can be significantly reduced by the presence of surrounding buildings and will be obviously decrease with the increase of C_A, but the positive peak wind pressure will increase in some cases. The environment with similar-sized buildings can lower the ambient pressure for a region below the general building height. Compared to a single building case, surrounding roughness arrangements can even increase the magnitude values of peak Cp's over 100%.

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REFERENCES

[1] T. C. E. Ho, D. Surry and A. G. Davenport. *Variability of low building wind loads due to surroundings*. Journal of Wind Engineering and Industrial Aerodynamics, 38, Issues 2-3, 297-310, 1991.

[2] D. Surry and J. X. Lin. *The effect of surroundings and roof corner geometric modifications on roof pressures on low-rise buildings*. Journal of Wind Engineering and Industrial Aerodynamics, 58, 113-138,1995

[3] H. Kiefer and E. J. Plate. *Modelling of mean and fluctuating wind loads in built-up areas*. Journal of Wind Engineering and Industrial Aerodynamics, Volume 74-76, 619-629,1998

[4] Cheng-Hsin Chang, Robert N. Meroney. *The effect of surroundings with different separation distances on surface pressures on low-rise buildings*. Journal of Wind Engineering and Industrial Aerodynamics, 91,1039–1050, 2003.

[5] *AIJ Recommendations for Loads on Buildings (in Japanese),* Architectural Institute of Japan, 2004

[6] American Society of Civil Engineers, *Minimum Design Loads for Buildings and Other Structures*, ASCE/SEI 7-05, American Society of Civil Engineers, New York, 2006.

[7] Holmes. J. D. and Best. R. J. *A wind tunnel study of wind pressures on grouped tropical houses*. Report no. 5/79. Department of Civil and Systems Engineering, James Cook University of North Queensland, Townsville, Queensland. Australia, 1979

[8] Hussam, M. and l.ee, B. E. *A wind tunnel study of the mean pressure forces acting on a large group of low-rise buildings*. J. Wind Engng. Indust. Acrodynam. 1980, 6. 207-225

[9] *Structural design actions, Part 2: Wind actions*, AS/NZS 1170.2:2002, Standards Australia/Standards New Zealand, 2002.

[10] B. G. Wirén. *Effects of surrounding buildings on wind pressure distributions and ventilative heat losses for a single-family house*. Journal of Wind Engineering and Industrial Aerodynamics, 15, 1983, 15-26