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Shielding effects on a tall building from a row of low and medium rise buildings

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Abstract. Wind loading of a tall building built amidst a group of buildings in urban environment is always greatly affected by shielding effects. Wind tunnel tests were carried out to assess the shielding provided by a row of low-rise or medium-rise buildings upstream a square-section tall building of height-to-breadth ratio 6. Mean and dynamic wind loads on the tall building were measured at different wind incidence angles and presented as interference factors (IFs). It is found that presence of a row of upstream buildings provides significant shielding to the tall building. At normal wind incidence, the mean along-wind loads and all components of fluctuating wind loads on the tall building are always reduced by shielding. Vortex shedding seems to still occur on the upper exposed part of the tall building but the vortex excitation levels are largely reduced. The degree of shielding is found to depend on a number of arrangement parameters of the row of upstream buildings. Empirical equations are proposed to quantify the shielding effect based on the wind tunnel data.

Keywords: tall buildings; shielding effect; interference; wind loads

1. Introduction

It is widely aware the wind effect on a building structure will be significantly modified by presence of surrounding buildings (e.g., Khanduri *et al*. 1998, Xie and Gu 2007, Yu *et al*. 2015, Hui *et al*. 2017, Zu and Lam 2018a,b). While undesirable magnification of wind loading may be induced by presence of upstream buildings, it is more typical to find the beneficial effect of sheltering for a tall building being surrounded by a group of other buildings. This is known as shielding effect.

For estimation of wind loads, some wind codes provide guidelines on the shielding effect. The Australian/New Zealand code (AS/NZS, 2011) uses a shielding multiplier to estimate the amount of wind load reduction. The main focus is the sheltering provided by buildings of equal height with the target building while the shielding effect from medium-rise or low-rise buildings is neglected. The shielding effect for free-standing walls and signboards with taller walls upwind is considered by the Eurocode (CEN, 2005). However, in most wind loading codes (e.g., ASCE 7-10, 2010; NBCC, 2010, BD-HK, 2004), the beneficial effect of shielding is not considered and conservative estimation may result for such building arrangements. The reason that shielding effect is not always considered in wind loading codes is that there are many parameters effecting the modification of wind loads induced by surrounding buildings and for some certain arrangements of structures wind loads can also be magnified (e.g., Pope 1994).

Shielding effects among a group of low-rise buildings have been investigated by many researchers (e.g., Hussain and Lee 1980, Kim *et al*. 2013, Wirén 1983). For wind load on high-rise buildings, Sakamoto and Haniu (1988) found that an upstream building can reduce the drag force of a downstream building to zero or even negative when the two buildings are closely positioned in the tandem arrangement and the shielding effect becomes weaker with increasing building distances. Based on the results of several wind tunnel tests, a regression equation was suggested by English (1993) to predict the mean along-wind force for two high-rise buildings in tandem arrangement. Xie and Gu (2004) found that two upstream tall buildings provide shielding effects for the mean along-wind force on a downstream tall building in most cases but a load increase up to 20% may occur by the channeling effect when three buildings were arranged side-by-side. Through a series of wind tunnel tests, Lam *et al.* (2008), Zhao and Lam (2008) and Lam *et al.* (2011) measured the modification of wind loads on a tall building in a group of same-shaped tall buildings arranged in various pattern and found that shielding effect remains the key interference effect.

In some Asian cities, many tall buildings are built in the city redevelopment to accommodate highly increasing population. This leads to a usual case that a tall building is erected amidst a group of older low-rise or medium-rise buildings. Although many studies have been conducted to investigate the interference effects induced by surrounding buildings in the past several decades, studies on such situation that a high-rise building surrounded by a group of low-rise or medium-rise buildings is rare (Lam *et al.* 2014). The present paper aims at a wind-tunnel investigation of the

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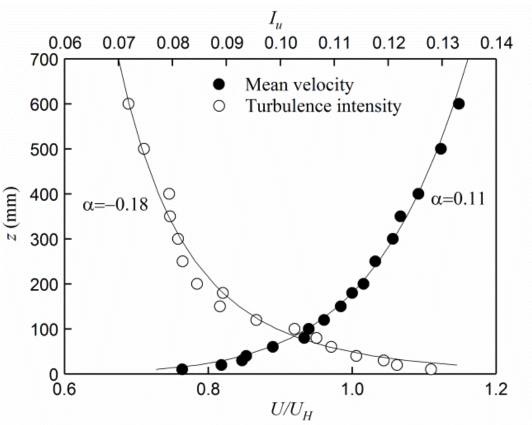
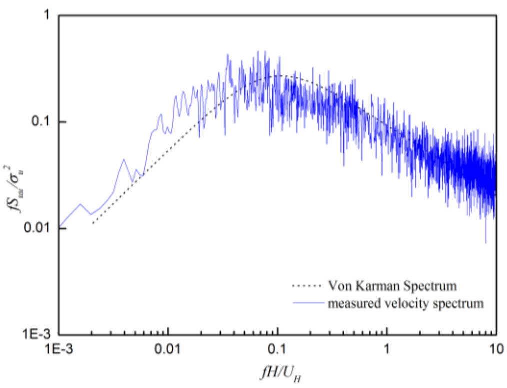
amount of wind load reduction on a tall building shielded by a row of low-rise and medium-rise buildings. Shielding effects are investigated for a number of building separation distances between the tall building and the row of upstream buildings with various wind incidence angles. The effects of varying parameters such as of spacing between buildings in the row, upstream building height, relative lateral position of the high-rise building and upstream buildings are also considered.

2. Experimental setup

Experiments were carried out in the boundary layer wind tunnel in the Department of Civil Engineering at the University of Hong Kong. The working section was 3.0 m wide and 1.8 m tall. Wind tunnel tests were carried out under simulated wind flow of the open land terrain, where the mean wind profile followed the power law with a power exponent of 0.11 (Lam *et al*. 2008). The flow in the wind tunnel was interpreted at a geometrical scale targeted at 1:300. The mean wind speed and turbulence intensity at the height of the building model during the test were U_H = 8.0 m/s and 0.072, respectively. The measured mean wind velocity and turbulence intensity profiles are shown in Fig. 1.



(a) Mean wind speed and turbulence intensity profiles



(b) Longitudinal turbulence spectrum

Fig. 1 Wind characteristics in wind tunnel

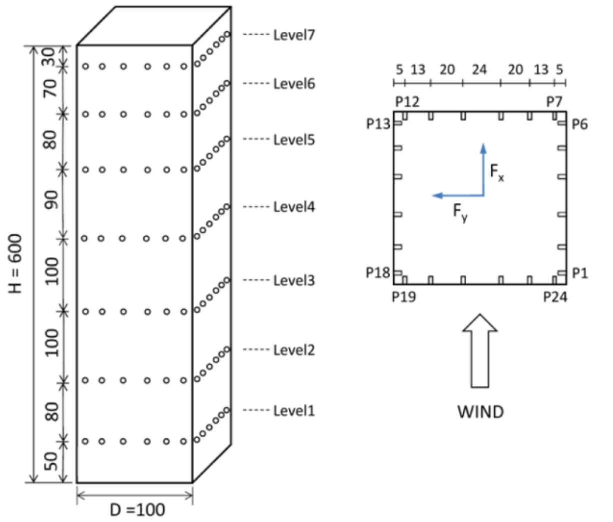


Fig. 2 Layout of pressure taps on building model (unit: mm)

The principal building model was a rigid pressure model with a square planform of breadth B = 0.1 m and height-to-breadth ratio H/B = 6. At the target geometric scale 1:300, the model represented a full-scale building of height 180 m and width 30 m. The Reynolds number was $Re = U_H B/\upsilon \approx 5.4\times10^4$. The building model was equipped a total of 168 pressure taps, 24 on each of its seven vertical layers (Level 1 to 7), as shown in Fig. 2. Pressure at all 168 taps on a building model was measured with a multi-point pressure scanning system (electronic pressure scanners and Initium system from PSI, Inc.) at a rate of 330 Hz/tap. Mean and fluctuating forces and moments on the test building in the along-wind, across-wind and torsional directions were obtained from the pressure data using pressure integration.

A number of test cases of the tall building being sheltered by a row of upstream low-rise or medium-rise buildings with various arrangement parameters were studied and they are shown in Table 1. The medium-rise (Cases 1-4) or low-rise (Case 5) buildings were also square in cross-section, but with breadth B_s = 0.133 m and height H_s = 0.3 m or 0.2 m (model scale), respectively. In the redevelopment of an older part of a city, it is common to find the erection of a new single tall building amidst existing medium-rise or low-rise buildings. To keep a similar plot ratio for the area, the width of the tall building will be smaller than those of the surrounding buildings. Therefore, a value of B/B_s = 3/4 was used in this study.

As shown in Fig. 3, the row of low-rise or medium-rise buildings were placed upstream to the principal tall building in a normal direction to the incoming wind. Two main categories of arrangements named “blocking” and “channeling” were studied. For the “blocking” category, five upstream buildings were included in the row and with the middle one positioned exactly upstream of the principal building (Case 1, 2 and 5). For “channeling” category, four buildings were used and the principal building faced the spacing between two buildings in the middle of the row and was likely to be exposed to the channeling effect (Case 3

Table 1 Test cases

Case	Lateral shift distance, d/B	Intra-spacing among shielding buildings, s/B	Height of shielding buildings, H_s/H	Axial separation distance, x/B
1	0	0.65	0.5	1.65, 3.45, 5.25, 7.05, 8.85 (Row 1 to 5)
2	0	1.3	0.5	
3[c]	0.975	0.65	0.5	
4[c]	1.3	1.3	0.5	
5	0	0.65	0.333*	

[c] "channeling" configuration, *low-rise sheltering buildings

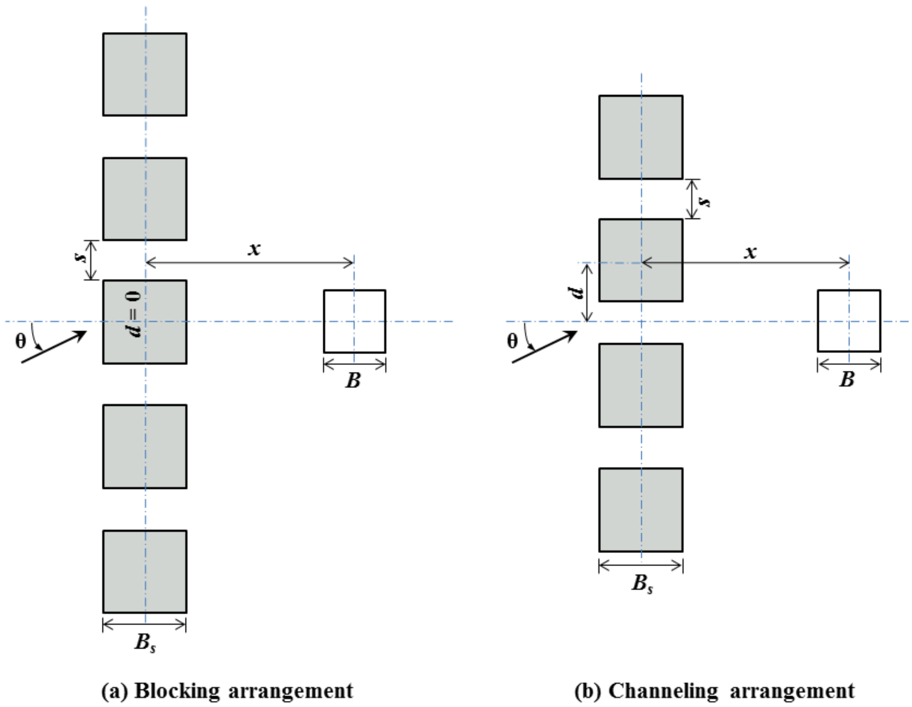


Fig. 3 Arrangements of surrounding buildings

and 4). In Table 1, the (lateral) shift distance d is used to represent the lateral distance between the centers of the middle building and the principal building. The effect of change the spacing s between upstream buildings were also considered by using two different spacing, $s = 0.5B_s$ and B_s. In each of all test cases, the row of upstream buildings was placed at one of 5 positions, named from "Row-1" to "Row-5" with different relative upwind separation distance x from the principal building. For each arrangement, measurements were made at wind incidence angles between 0° and 45° with 5° intervals.

3. Results and discussions

The results are summarized in the form of interference factor that depicts the change of aerodynamic force acting on the principal building due to shielding or interference from the surrounding buildings. The interference factor (IF) (or buffeting factor) suggested by Saunders and Melbourne (1979), is defined as

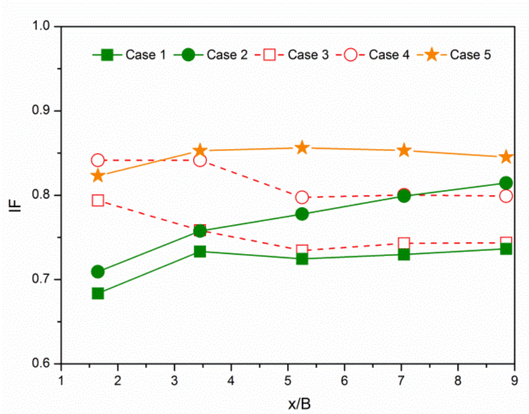
$$\text{Interference factor (IF)} = \frac{\text{Wind load (interfering buildings present)}}{\text{Wind load (isolated building)}} \quad (1)$$

The measured IF results for mean and RMS (root-mean-square value of fluctuating component) along-wind moments on the principal building with the medium-rise and the low-rise surrounding buildings under the normal wind incidence of θ = 0° are plotted against the relative separation distance x/B in Figs. 4 and 5, respectively. For both "shielding" and "channeling" arrangements, a significant decrease in the mean along-wind load (IF < 1) on the principal building is observed due to shielding effect provided by the upwind buildings (Fig. 4a). It is obvious that the IFs due to the low-rise surrounding buildings (Case 5) is lower than unity by clearly smaller amounts than the sheltering provided by the corresponding arrangement of medium-rise buildings (Case 1), confirming that medium-rise upstream buildings can provide stronger shielding than low-rise buildings. As expected, the difference between unity and IFs of the "blocking" arrangement (Cases 1 and 2) decreases with increasing axial separation distance (between the principal building and the upstream buildings). However, in the "channeling" arrangement (Cases 3 and 4), the differences of IFs from unity decrease with increase in separation distance. At large separation distances, $x/B \geq$ 7.05, the degrees of shielding provided by the two categories are similar but when the row of upstream buildings are closely positioned with $x/B \leq 3.45$, IFs of the "blocking" cases are smaller (i.e., stronger shielding) than those of the "channeling" cases. On the whole, the shielding effect on the mean along-wind loads does not vary significantly with change in axial separation distance. For Case 1 to Case 5, IF only varies between 073 ~ 0.79, 0.80 ~ 0.84, 0.68 ~ 0.74, 0.71 ~0.81 and 0.82 ~ 0.86, respectively.

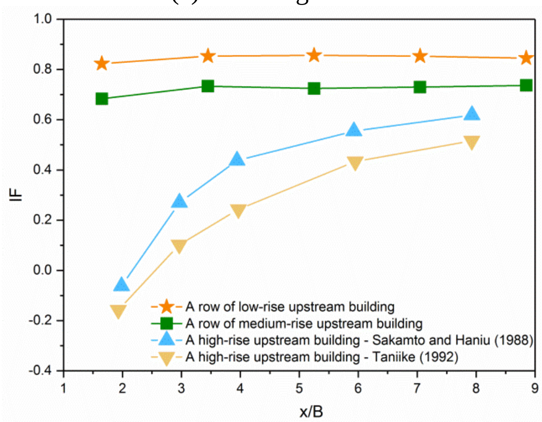
For a tall building being shielded by a single upstream building of the same height, English (1993) asserts that the shielding effect for mean along-wind load on the downward building decreases significantly as the separation distance increases. Fig. 4b compares IFs of the mean along-wind load in the present study with the IF results from previous studies on a tall building directly downstream of a single upstream building with the same height. It is evident that although the degree of shielding provided by a group of medium- or low-rise buildings is weaker than a single upstream high-rise building, several buildings in an upstream row provide a more stable shielding effect on the downstream building that is less sensitive to the separation distance than a single upwind building.

For the RMS along-wind load, the IFs of all cases are also smaller than unity (Fig. 5). The IFs of all the five cases are quite close to each other for the same separation distance. The degree of shielding decreases gradually with the increase of separation distance which agrees well with the shielding provided by one upstream building (Saunders and Melbourne, 1979). The range of IFs is between 0.7 and 0.89, meaning that the RMS along-wind moments are reduced by 11-30% as a result of shielding.

For the fluctuating across-wind moment (Fig. 6), the IFs are smaller than unity for all the cases and significant reductions by up to 61% and 49% are provided by the medium- and low-rise buildings, respectively in "Row 1". This universal deduction of dynamic wind loads is distinct from the interference effect from a single upwind building which, has been reported in the literature, to cause magnification of the fluctuating wind forces on the downstream building in some cases (Mara *et al.* 2014, Zu and Lam 2018b). When the axial separation distance increases in Fig. 6, the IFs of RMS across-wind load increase gradually for all test cases. With different intra-spacing among the upstream buildings, Cases 2 and 4 with the larger spacing leads to larger IF values (weaker shielding) than Cases 1 and 3 with the smaller spacing except for "Row 1". Similar with the results of mean along-wind load, shielding effect from the low-rise upstream buildings are weaker than that from the medium-rise buildings. The IF curves of RMS torsion are plotted in Fig 7. IFs for all test cases are smaller than unity and the shielding effect becomes weaker with the axial separation distance getting larger except for Row 2 of Cases 3 and 4. These are the "channeling" arrangement and the principal building is located near to the ends of the near wakes of two upstream buildings. Flow oscillations in the near wakes may cause unequally fluctuating wind forces on the two sides of the principal buildings and bring the IFs nearer to unity.



(a) Shielding effect



(b) Comparison with single upstream high-rise building

Fig. 4 IFs of mean along-wind moment

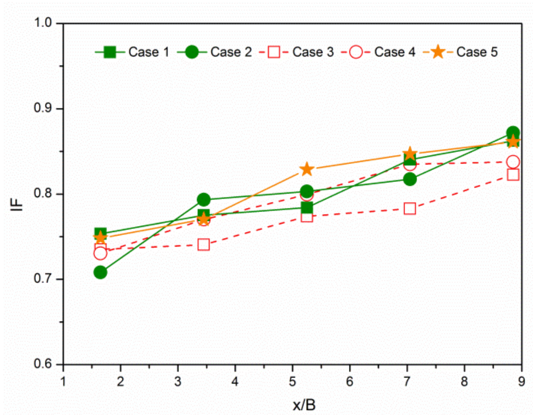


Fig. 5 IFs of RMS along-wind moment

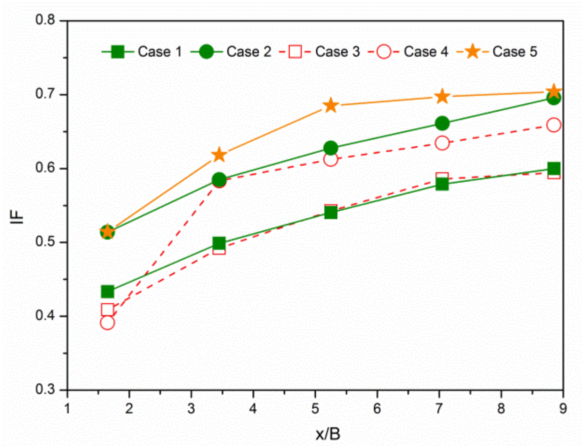


Fig. 6 IFs of RMS across-wind moment

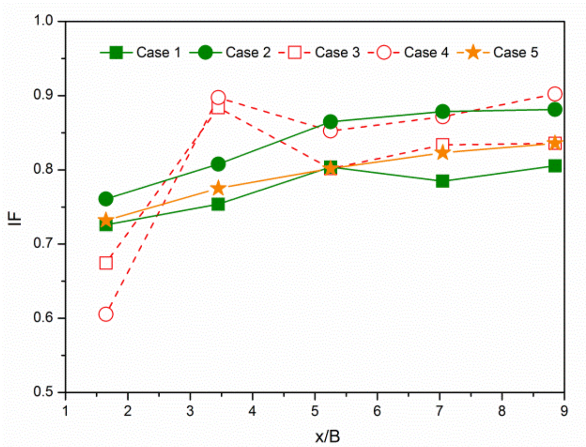


Fig. 7 IFs of RMS torsion

The distributions of mean pressures on the windward walls of the tall building are presented in Fig. 8. For the "blocking" cases, obvious shielding effect can be observed. The wind pressures on the lower part can become negative when the upstream buildings are very close to the principal buildings (Figs. 8(b) and 8(d)). With larger axial separation distances (Figs. 8(c) and 8(e)), the influence of the upstream buildings becomes weaker but can still mainly affect the lower part of the tall building. For the "channeling" cases (3 and 4) with a small separation distance, wind can flow through the spacing between two upstream buildings and onto the principal building. Therefore, the deduction of wind pressures on the windward wall is much smaller than the "blocking" configurations, especially for Case 4. In all test cases, no obvious magnification of mean wind pressures can be observed. At the longest axial separation ("Row-5"), it can be seen that the mean wind pressure distribution of Case 3 (Fig. 8(g)) is quite similar with that of Case 1 (Fig. 8(c)), suggesting similar shielding effects provided by the far away upstream buildings in "blocking" and "channeling" arrangements.

Power spectra of the overturning moments along the two building body axes under normal wind incidence are shown in Figs. 9 and 10, respectively. The results of different axial separation distances are found to be similar, so power spectra are mainly presented for "Row-1". The power spectral densities are shown as the power of moment coefficient against Strouhal number so that comparison of the RMS power levels can be revealed directly from the spectrum curves

$$\frac{nS_{MM}(n)}{\left(\frac{1}{2}\rho \bar{U}_H^{\,2} BH^2\right)} = f\left(\frac{nB}{\bar{U}_H}\right) \tag{2}$$

For the across-wind moment spectrum of M_x, a sharp spectral peak due to vortex excitation is observed at the expected Strouhal number of $St = nB/U_H \approx 0.1$ on the single isolated tall building (Fig. 10). With the presence of the upstream building row, the vortex excitation peak is still obvious in the across-wind moment spectra, although the spectral peak is less sharp and occurs at a lower power spectral level (Fig. 10). For a high-rise building sheltered by a single identical upstream building, it is believed that the periodic vortex shedding of the downstream building is totally impaired by the upstream building and the fluctuating energy in the across-wind direction is mainly from the vortex shedding from the upstream building. In the present study, with a row of upstream buildings with lower heights, there is no obvious spectral peak observed in the along-wind spectra of all test cases in Fig. 9 to suggest any dominant quasi-periodic fluctuations caused by the upstream medium-rise buildings in the incoming flow approaching the tall building. Therefore, it can be deduced that the remaining fluctuating energy of the across-wind spectral peak in Fig. 10 should come from vortex shedding from the principal building itself rather than from the upstream buildings. With presence of the row of upstream buildings, periodic vortex shedding from the still occur on the upper part of the building (Lam *et al*. 2014).

The cause of the spectral peaks in Fig. 10 being due to vortex shedding from a part of the tall building is further supported by a number of observations as follows. In the "blocking" configurations, the tall building shielded by the low-rise buildings (Case 5) experiences higher fluctuating across-wind loading energy than by the medium-rise buildings (Cases 1 and 2). The vortex excitation peak in the "Row-1" cases has lower spectral power than the "Row-5" cases. The spectral peaks of Cases 3 and 4 are less sharp than those of Cases 1 and 2, indicating that severer impairment of periodic vortex shedding is induced by the "channeling" arrangement than the "blocking" arrangement.

Shielding from surrounding buildings also leads to reduction in the spectral levels of the along-wind moment M_y (Fig. 9) but the reduction occurs equally over all frequencies. The spectral distribution thus remains largely unchanged. The modifications to the along-wind moment spectra are similar for the "blocking" and "channeling" configurations. The spectral power levels of "Row-5" are slightly higher than that of "Row1", which agrees with the results in Fig. 5.

The consequent modifications of wind-induced dynamic responses on the principal tall building are estimated from the measured integral fluctuating base moments together with the dynamic properties of the building (Tschanz 1982,

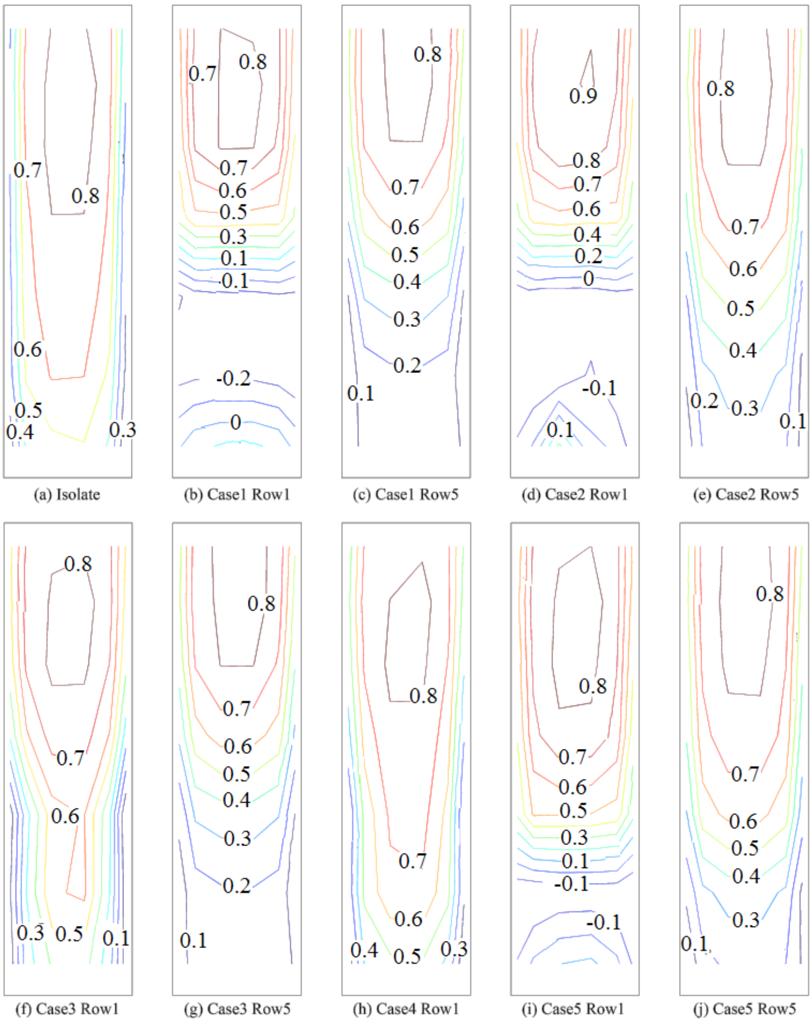


Fig. 8 Pressure distribution on windward walls

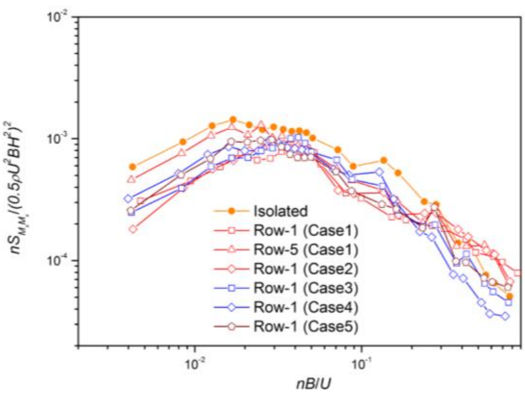


Fig. 9 Nomalized spectra of along-wind moments

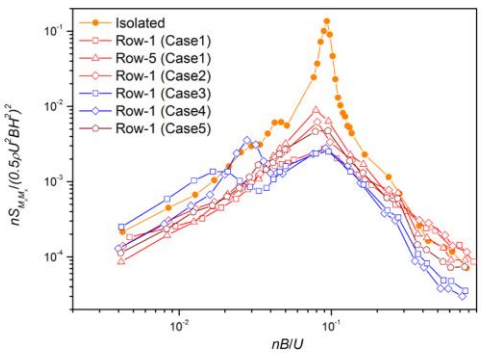


Fig. 10 Nomalized spectra of across-wind moments

Tschanz and Davenport 1983). The tall building is assumed to possess ideal mode shapes, that is, linear and uncoupled, for the fundamental modes of vibration along the two sway directions x and y with same natural frequencies of $n_{0,x}$ = $n_{0,y}$ = 0.2 Hz (full-scale value). The response curves of building deflections or accelerations with reduced velocities, $V_R = U_H/n_0B$, have similar shapes at different values of damping ratio (Lam *et al.* 2008). Thus, a comparison study can be made using either deflections or accelerations, or any values of damping. In this study, the shielding effect on dynamic response is studied from building deflections with a damping ratio $\zeta = 0.03$.

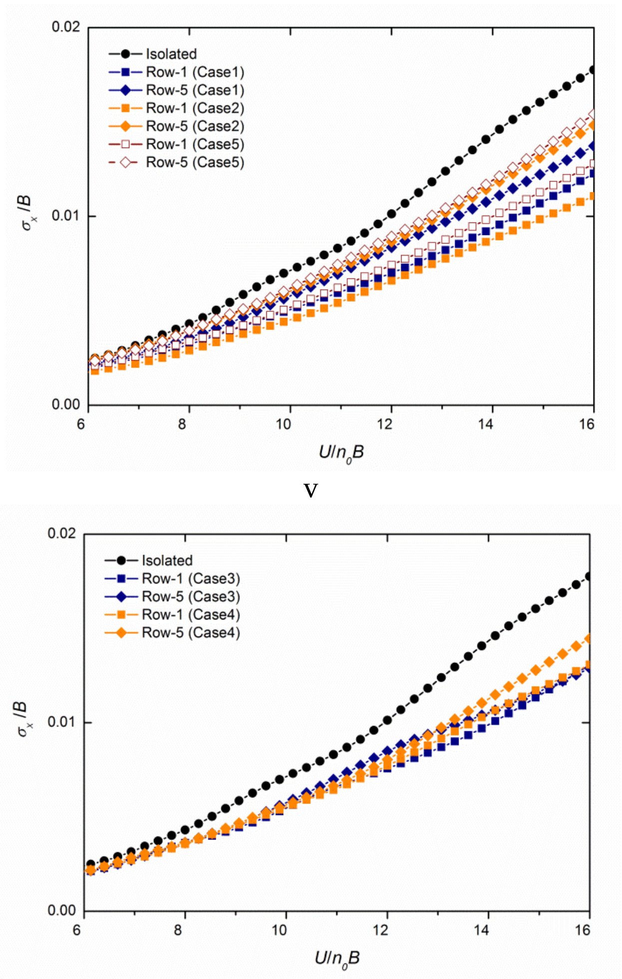


Fig. 11 Wind-induced dynamic responses of along-wind deflections at different reduced velocities at normal wind incidence

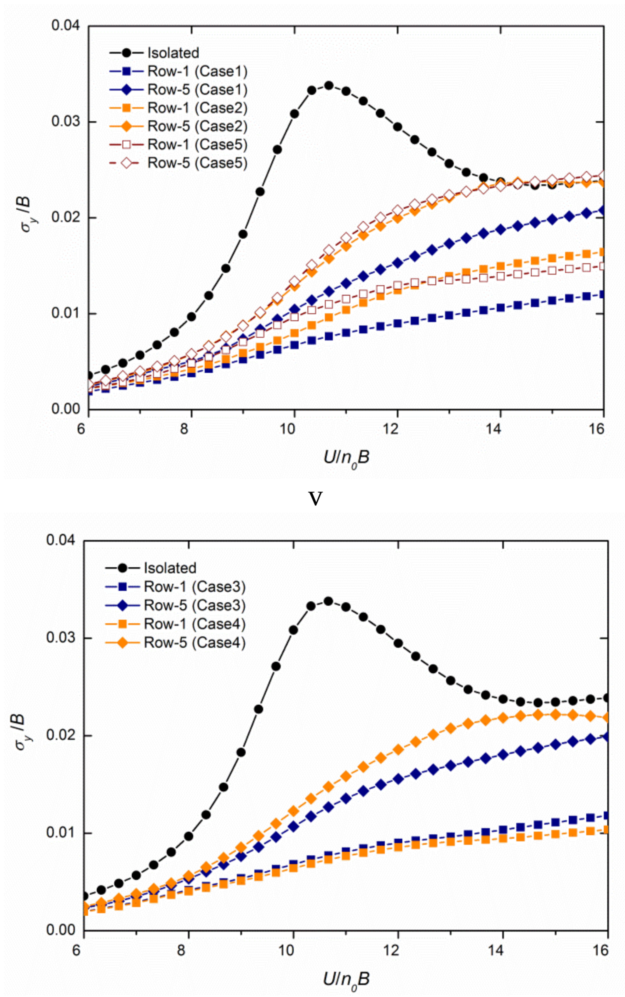


Fig. 12 Wind-induced dynamic responses of across-wind deflections at different reduced velocities

Fig. 11 presents the along-wind RMS building deflections against reduced velocities V_R at the normal wind incidence. The curves of along-wind responses reflect a monotonic increase of building deflections with wind speed for the tall building both with and without upstream buildings. The increase of RMS building deflections with reduced velocity has been found to be well described by a power relationship $\sigma_x/B = V_R^{2.1}$ for the isolated single building (Kareem *et al.* 1978). In the present situation of being surrounded by a row of upstream medium-rise buildings, the power law relationship is also found to well describe the variation of along-wind RMS deflection with reduced velocity. The power exponent obtained from curve fitting changes to 1.9 to 2.0 depending on the arrangement parameters of the sheltering buildings. For all arrangements of upstream buildings, along-wind dynamic responses of the tall building are reduced to various extents. It can be seen that a smaller axial separation distance ("Row-1") leads to a larger reduction of dynamic response than a larger separation distance ("Row-5"). Consistent with wind loads modification, it is observed that the low-rise buildings provide weaker shielding to the building responses than the medium-rise buildings by comparing the results of "Case-1" and "Case-5". In all test cases, there is no noticeable resonance phenomenon in the deflection responses. This suggests that presence of a group of medium- or low-rise upstream buildings will not contribute periodic wind loads on the principal, which may lead to extra resonance response in the along-wind direction.

The across-wind RMS building deflection responses of the tall building are shown in Fig. 12. The curves of across-wind deflection for the square building exhibit the expected resonance at reduced velocity near 10 which is the reciprocal of the Strouhal number of the spectral peak in the across-wind moment spectra. Near this wind velocity, the frequency of vortex excitation matches the natural frequency n_0 of the building. With the impairing of coherent across-wind excitation forces on the principal tall building brought about by the upstream buildings (Fig. 10), the resonant across-wind response behavior is found to be decreased significantly for all test cases. The peak response at reduced velocities near 10 is not present with the sheltering buildings present upstream. With medium-rise upstream buildings, the RMS across-wind building deflections can be reduced by up to 58% to 79%, depended on the upstream arrangement parameters, at reduced velocities around 10. Similarly with the along-wind response, strongest reduction of dynamic response occurs when the upstream buildings are closely located with the tall building. With the increase of axial separation distance, the reduction becomes smaller. As expected, a stronger shielding effect is provided by the medium-rise buildings than the low-rise buildings.

Tests have also been made under different angles of wind incidence. The changes of shielding effects on the mean and the RMS along-wind moments due to the change of wind direction are shown in Figs. 13 and 14. For all test cases, both mean and RMS along-wind moments are reduced by presence of the upstream buildings under all wind incidence angles from 0^{o} to 45^{o}, with the strongest shielding effect occurring at 0^{o}. For the RMS across-wind moment (Fig. 15), the upstream buildings can provide notable shielding under wind directions within 15^{o} from normal incidence while at larger wind angles, the shielding effect is negligible. A similar situation is observed for the RMS torsion in Fig. 16. Only within 10^{o} from normal wind incidence, the RMS torsion is deduced by the shielding effect, while at larger wind angles the RMS torsion on the downstream building is equal or even larger than that on the isolated building.

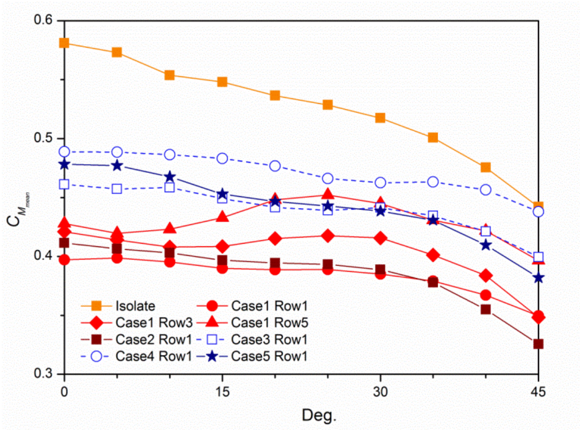


Fig. 13 Wind angle variations of mean along-wind moment coefficients

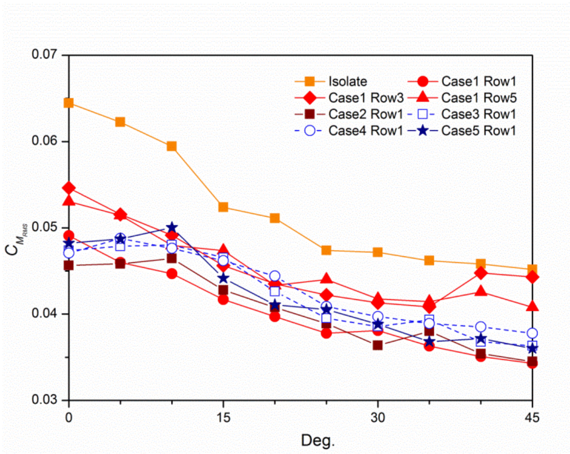


Fig. 14 Wind angle variations of RMS along-wind moment coefficients

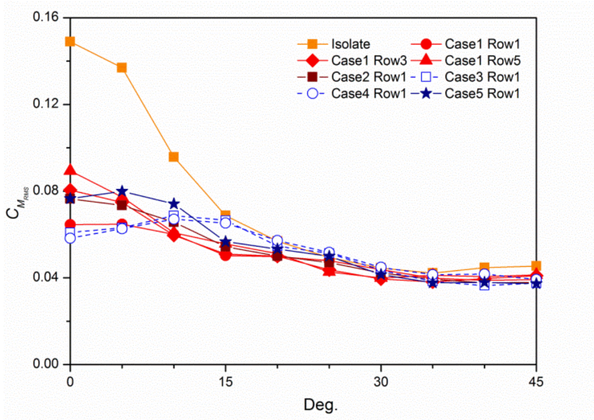


Fig. 15 Wind angle variations of RMS across-wind moment coefficients

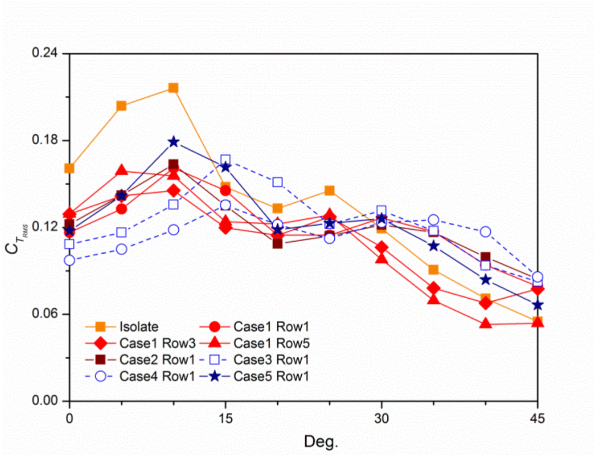


Fig. 16 Wind angle variations of RMS torsion coefficients

According to the wind tunnel experiments in the present study, the degree of shielding effect on the target tall building due to a row of upstream buildings is governed by a number of parameters which include axial separation distance x, spacing among shielding buildings s, shift distance d and height of shielding buildings H_s

$$IF = \phi\left(x/B, s/B, d/B, H_s/H\right) \tag{3}$$

Based on the IFs measured under various combinations of all these parameters as shown in Table 1, the following formulae for IFs of mean and RMS along-wind moments, RMS across-wind moment and RMS torsion are obtained by multiple linear regression, respectively:

$$IF_{\overline{M}_{along}} = 0.0018x/B + 0.0770s/B + 0.0342d/B - 0.7484H_s/H + 1.0362 \tag{4}$$

$$IF_{M'_{along}} = 0.0150x/B + 0.0251s/B - 0.0101d/B - 0.1451H_s/H + 0.7644 \tag{5}$$

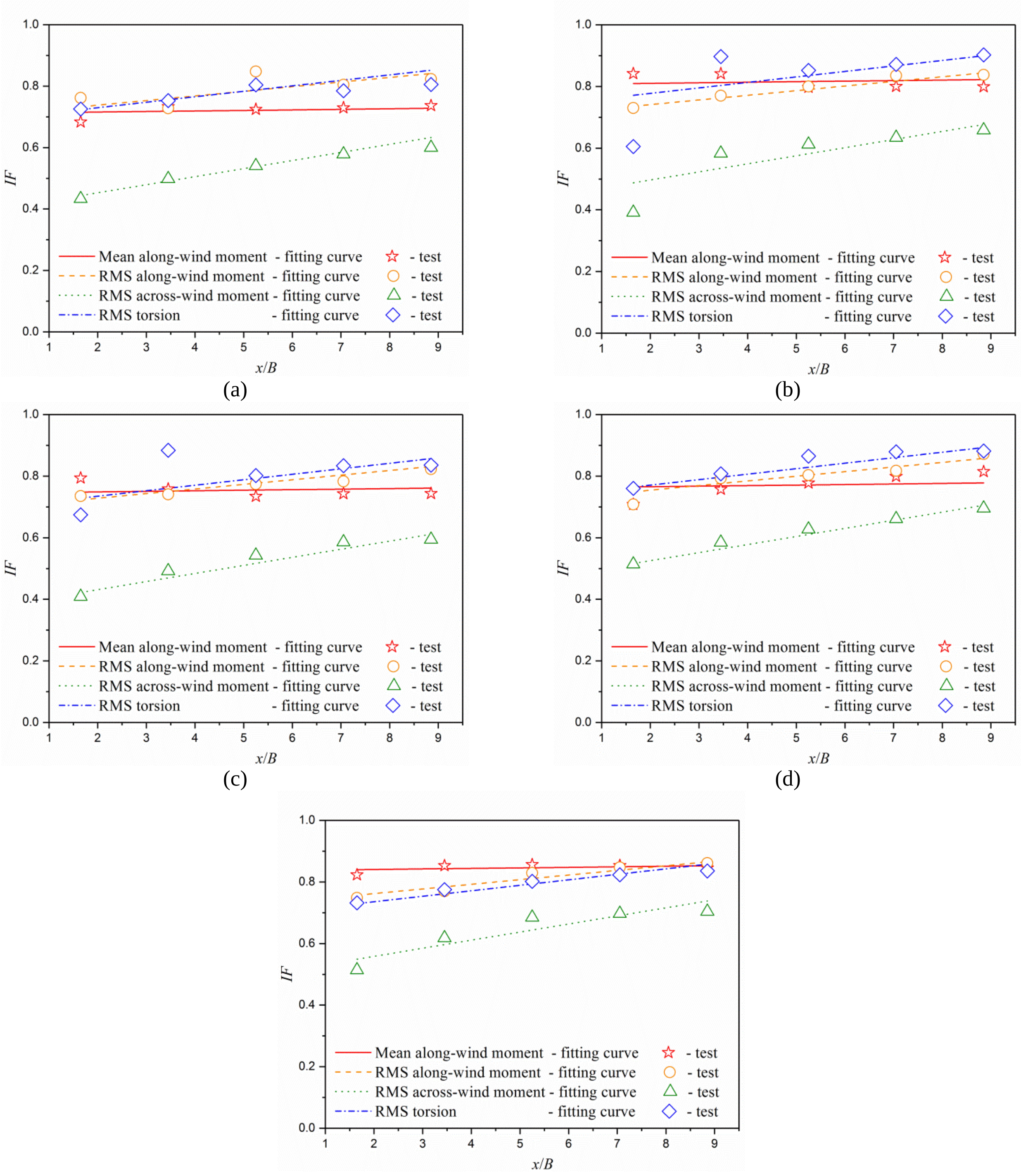


Fig. 17 Multiple linear regression analysis of wind loads on tall building of various configurations: (a) Case 1; (b) Case 2; (c) Case 3; (d) Case 4; (e) Case 5

$$IF_{M'_{across}} = 0.0263x/B + 0.1114s/B - 0.0221d/B - 0.6328H_s/H + 0.6445 \tag{6}$$

$$IF_{T'} = 0.0178x/B + 0.0632s/B - 0.0052d/B - 0.0356H_s/H + 0.6709 \tag{7}$$

where B and H are the width and height of the principal building. The results of the multiple regression analysis are shown in Fig. 17. The corresponding correlation coefficients of the four formulas are 0.89, 0.89, 0.94 and 0.71, respectively. The standard errors of IF are 0.025, 0.023, 0.033 and 0.056 for the four regression formulae, respectively. Generally the regression formulae of along-wind and across-wind loads have good precision relative to the experiment data. The largest error occurs in the formula for the RMS torsion. In all these formulae, the multipliers of the axial separation distance x and the intra-spacing among upstream buildings s are positive, indicating that the shielding effect provided by the upstream building becomes weaker with increase in separation distance or intra-spacing among upstream buildings in the row. The multiplier of the shift distance d is positive in the formula of mean along-wind moment but negative in those of RMS along- and across-wind moments and torsion, reflecting the fact that the "channeling" arrangement leads to a lower degree of shielding for mean along-wind moment but relatively higher degree of shielding for fluctuating wind loads than the "blocking" arrangement. As the IFs of all test cases with the low-rise upstream buildings are smaller than those with the medium-rise buildings, the multiplier of the upstream building height H_s is negative.

4. Conclusions

The degrees and characteristics of shielding effects provided by a row of low-rise or medium-rise buildings of various arrangements and varying separation distances upwind of a principal tall building are investigated by wind tunnel tests. The tall building has a square section and height-to-breath ratio 6. The upstream buildings have a breadth 1/3 times larger and height at 1/2 or 1/3 times that of the tall building. The following conclusions can be drawn from this investigation.

Under normal wind incidence, it is found that presence of a row of upstream buildings always provides significant shielding to the downstream tall building, both for mean and RMS values of all components of wind load. This is different from the interference effect from a single upstream building, which can often increase the dynamic wind loads by introducing turbulence in the approaching wind through the mechanism of wake buffeting.

The degree of shielding is found to be determined by the combinations of several arrangement parameters of the upstream sheltering buildings. These include axial separation distance between the sheltering buildings and the principal building, intra-spacing among shielding buildings in the row, lateral shift distance and height of the shielding buildings. Based on the wind tunnel test results, multiple regression equations are proposed to present the relationship of interference factors for shielding and the arrangement parameters of upstream buildings.

The pressure distribution on the lower part of the windward wall of the principal tall building is found to be severely affected by the upstream buildings, especially with smaller axial separation distances which can turn the wind pressures from positive to negative. The "channeling" and "blocking" arrangements can lead to distinctly different wind pressure distributions on the principal building when the separation distance is small. With larger separation distances, the influence of these two arrangements becomes similar.

Both the rows of medium-rise and low-rise buildings are expected to significantly lower the strength and coherence of regular periodic vortex shedding from the tall building. This leads to a large reduction in the level and sharpness of the narrow-banded spectral peak of vortex excitation in the measured across-wind load spectra of the tall building relative to the single isolated building case. The consequent wind-induced resonant dynamic responses at reduced velocities around 10 are largely suppressed due to the shielding effect.

Under wind incidence angles from 0^o to 45^o, both the mean and the RMS along-wind moments are reduced by the presence of the upstream buildings and the strongest shielding effect occurs at normal wind incidence. For the RMS across-wind and torsional moments, the upstream buildings can provide shielding only for wind direction between 0^o and 15^o while at larger wind angles, negligible shielding effect is found.

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