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Reprinted from

Advances in Structural Engineering

Volume 14 No. 2 2011

MULTI-SCIENCE PUBLISHING CO. LTD.
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Wind Loads and Responses of Two Neighboring Dry Coal Sheds

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(Received: 6 October 2009; Received revised form: 7 June 2010; Accepted: 9 June 2010)

Abstract: This paper discusses an investigation into the interference effects on the wind-induced responses of a dry coal shed structure used for depositing coal stacks. Two interference factors, a nearby shed and coal stacks inside the shed, are considered. A wind tunnel test was conducted to obtain wind pressure distributions on the roof surface of the shed, and the results are briefly analyzed. The characteristics of the wind-induced responses of the structure and the effects of interference factors are then illustrated. The paper places emphasis on wind-induced responses and interference factors variations, and points out the situations when the maximum interference effects occur. The effects of an adjacent shed and incident wind direction are more pronounced than the spacing of adjacent sheds and coal stacks inside the shed. The most unfavorable results appear when an oblique wind blows at 45° span-wise with no interfering shed nearby, but when there is low coal stack inside. Values of the interference factor are also slightly higher than 1.0 for the maximum absolute peak responses in all cases investigated. This indicates that interference conditions magnify the peak responses of an isolated roof only minimally.

Key words: dry coal shed, interference effect, wind tunnel test, interference factor, wind-induced response.

1. INTRODUCTION

Historically, wind-induced interference effect on buildings has always been a concern. Flow interference occurs when two or more buildings are built in close proximity. Wind loads on building surfaces and wind-induced responses of building structures typically change especially when compared with wind effects on isolated single structures. Interference effects on the wind loading on buildings have been reported in the literature for decades. Some results are summarized in a report of Khanduri (1998), who performed a review of this topic. However, most of the researches on interference effects between buildings focused on tall buildings only. Earlier studies on tall buildings paid attention only to mean wind pressures and wind forces (Blessman 1979; Saunders 1979). Wind-induced dynamic responses of tall buildings were also investigated later. Lumped-mass aero-elastic models (Bailey and Kwok 1985; Zhang *et al.* 1994) and base-balance technique (Taniike 1992) were used to explain the mechanism of interference. The artificial neural networks method was used to analyze experimental data, and along-wind and across-wind dynamic interference factor contour maps were obtained for use as references for wind load design codes for buildings (Huang and Gu 2005). The most important findings mentioned above involved only two buildings. Some researchers investigated the interference effects among more than two tall buildings. The along-wind dynamic interference effects for two and three tall buildings were investigated through a series of wind tunnel tests on typical tall building models using the high frequency force balance technique (Gu and Xie 2005). Xie and Gu (2007) adopted an effective method to represent the distribution of the envelope of the

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Associate Editor. Y. Xia.

interference factors among three tall buildings. Simplified formulae were proposed to evaluate the wind-induced interference effects among three tall buildings. Lam (2008) analyzed the interference effects among five close spaced square-plan tall buildings arranged in a row through wind tunnel experiments.

Research on the interference effects involving low buildings was also carried out. Investigations on the significance of surrounding buildings on the wind pressure on low-rise buildings were reported (Hussain 1980; Tsutsumi 1992). Stathopouls (1984) presented the results of an experimental study carried out in a boundary layer wind tunnel to determine the wind loads on low buildings of different geometries in the presence of a tall building nearby (placed in various relative locations). Results showed significant adverse effects (wind load amplifications higher than 200%) for particular building proximity configurations. Ho *et al.* (1991) studied the effects of surroundings on the wind loads on flat-roof low buildings with different types of immediate surroundings. The mean wind pressure acting on the building decreased with an increase in the surrounding obstructions while the unsteady pressure increased. Ahmad (2001) selected a hip roof building model with a 30° roof slope as the test building to examine interference with a similar building, as well as three similar buildings placed upstream in 15 different locations. Shielding, for most of the interfering building locations, was observed. Maximum enhancement found among minimum wind coefficients was 73%, while maximum shielding found for mean wind coefficients was 69%. Researchers are seldom concerned about wind-induced responses under interference conditions, although interference effects on wind loading research have been emphasized above. In addition, the structures investigated were generally low-rise buildings that are not wide span. The diversity of geometric profiles and the structural responses of large-span roofs are the main reasons for the research which has occurred. Tall buildings, in contrast to low rise large-span roof buildings, have a simple profile, and structural engineers usually place more emphasis on specific responses such as top displacement, base shear, and base overturning moment.

This paper discusses the interference effects on the wind-induced responses of a dry coal shed structure situated in a region often devastated by hurricanes. A coal shed is commonly built near another one, and coal stacks are laid inside the sheds. These two interference factors, a nearby shed and coal stacks inside the sheds, were taken into account. A cylindrical shell is the usual type of roof used to cover a coal store and side-by-side positioning of sheds is the most common arrangement in China. In fact, there are no wind loading codes or standards giving guidance on the interference effects arising from sheds built closely together with coal stacks inside. Though the purpose of paper is not to provide a general guide, the results for the coal sheds might provide useful references for similar situations.

First, a brief introduction to the wind tunnel test and the characteristics of wind-induced responses of structures calculated in the frequency domain using wind pressure data obtained from the wind tunnel experiment are given. Second, interference factors for wind-induced responses are analyzed. Those situations with the most unfavorable responses or maximum interference effects are pointed out. The paper focuses on the variation patterns in the wind-induced responses caused by complexities due to the range of parameters involved, and does not attempt to describe in detail the characteristics of wind pressure near the surfaces of the sheds. Wind pressure distributions on the surfaces of the sheds for some specific wind directions are then analyzed to explore the interference mechanism to some extent.

2. WIND TUNNEL EXPERIMENT

The prototype coal shed used in the experiment was a cylindrical shell with a span of 103.0 m, a height of 40.0 m, a length of 140.0 m, and a rise-span ratio of 0.39. Wind can cause severe damage to the structure because it is located in a hurricane-prone region in China.

The influences of two interference factors have been evaluated as indicated above. One interference factor is an interfering adjacent shed, which has the same geometrical profile as the principal shed. Only a side-by-side arrangement of the two sheds was studied. An isolated shed with no inside coal stack (regarded as a non-interference case) was also tested. A shed is defined as “nearby” when the spacing between the two sheds, *D*, equals 16.0 m. A “distant shed” occurs when *D* equals 32.0 m. Coal stacks inside the shed are another interference factor. The inside coal stack is properly simulated. The cases defined as “without stack,” “low stack,” and “high stack” have coal stack heights, h, of 0, 6.0, and 12.0 m, respectively. The length of stack is set equal to that of the shed. Eighteen cases were studied for two types of terrain category (labeled “A” and “B”) that were simulated (Table 1).

The wind tunnel test was performed in a TJ-2 Boundary Layer Wind Tunnel in Tongji University to obtain the pressure distribution on the roof surface. The wind tunnel working section is 3.0 m wide and 2.5 m high. The geometrical scale used was 1:150. A total of 430 measuring taps were arranged in a grid pattern on both the upper and bottom surface of the roof, totaling

Table 1. Eighteen cases in the wind tunnel test

No.	Case	No.	Case
1	terrain category A, distant shed, high stack	10	terrain category B, distant shed, high stack
2	terrain category A, distant shed, low stack	11	terrain category B, distant shed, low stack
3	terrain category A, distant shed, without stack	12	terrain category B, distant shed, without stack
4	terrain category A, nearby shed, high stack	13	terrain category B, nearby shed, high stack
5	terrain category A, nearby shed, low stack	14	terrain category B, nearby shed, low stack
6	terrain category A, nearby shed, without stack	15	terrain category B, nearby shed, without stack
7	terrain category A, isolated shed, high stack	16	terrain category B, isolated shed, high stack
8	terrain category A, isolated shed, low stack	17	terrain category B, isolated shed, low stack
9	terrain category A, isolated shed, without stack	18	terrain category B, isolated shed, without stack

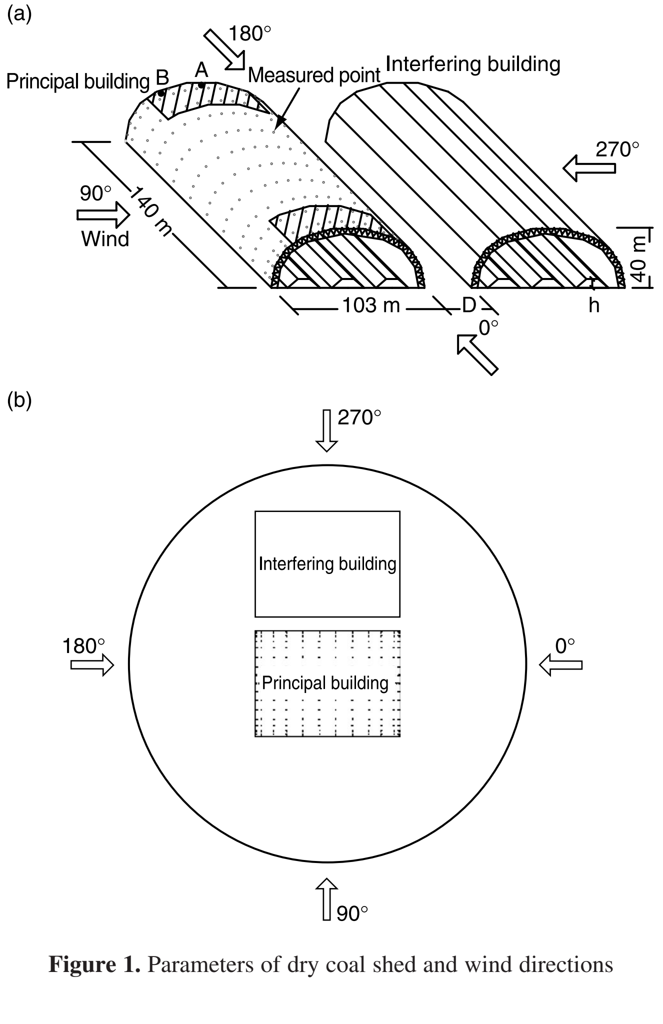


Figure 1. Parameters of dry coal shed and wind directions

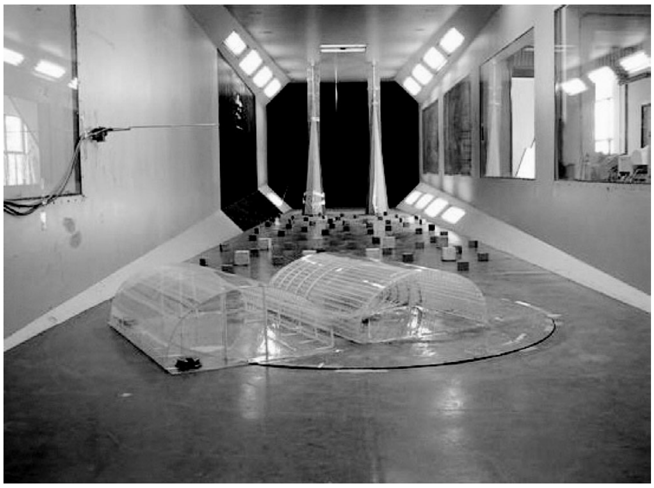
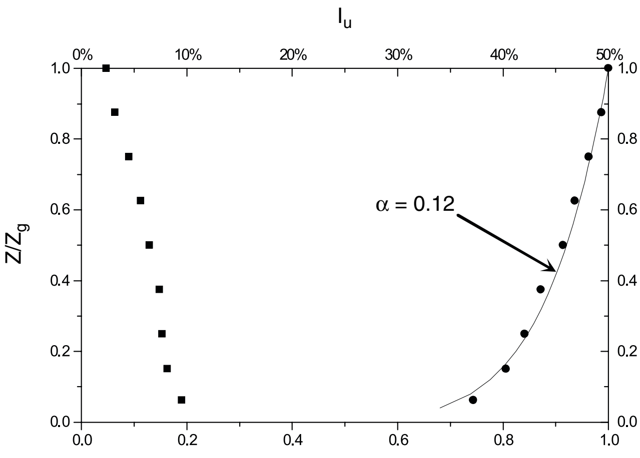


Figure 2. Rigid model for wind tunnel test

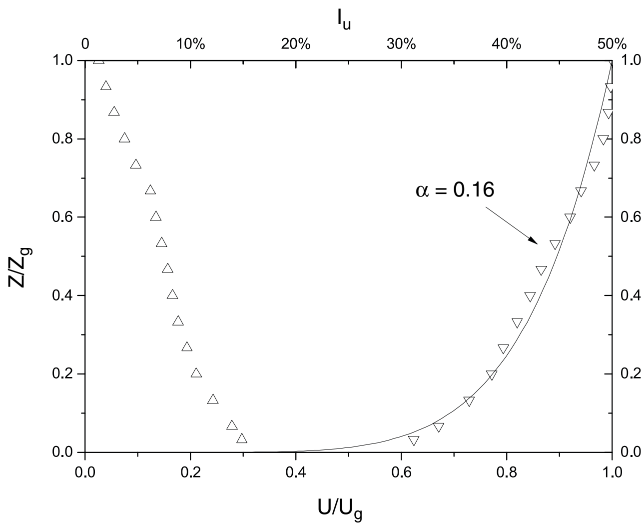
215 measuring points. Fluctuating wind pressures at 300 Hz were simultaneously measured at the 430 measuring taps on a rigid model of the roof. The azimuth range of 90°–270° was taken because of the symmetry of the shed, and the interval between angles was 15°. The 90° wind direction was defined as wind parallel to the span-wise direction of the roof. The parameters of the roof and wind directions are shown in Figure 1. Pressure taps were connected with a measurement system made of PVC tubing. Signals were modified using the transfer function of the tubing systems to avoid distortion of the dynamic pressure. Figure 2 presents a photograph of the rigid model of the roof, where the principal and interfering sheds are presented (same as in Figure 1).

The wind fields of terrain categories A and B, in accordance with the Chinese Code (GB5009-2001 2006), were simulated with a standard spire-roughness arrangement on the wind tunnel floor. The exponent of the mean wind speed profile for terrain categories A and B were 0.12 and 0.16, respectively. The reference wind speed at a height of 1.0 m (equivalent to 150.0 m in the atmospheric boundary layer) in the wind tunnel (measured using a pitot tube) was 12.0 m/s, indicating that the velocity scale for the terrain categories A and B was 1: 4.13 and 1: 3.72, respectively. The turbulence intensities at the height of the roof top were about 10% and 15% for A and B terrains, respectively. The profiles of mean velocity U normalized by the free-stream velocity U_G and the turbulence intensity used in the wind tunnel test are shown in Figure 3. Power spectra at the height of the roof top in the wind tunnel are shown in Figure 4.

Wind pressure obtained from the pitot tube was used to calculate the non-dimensional pressure coefficients. The

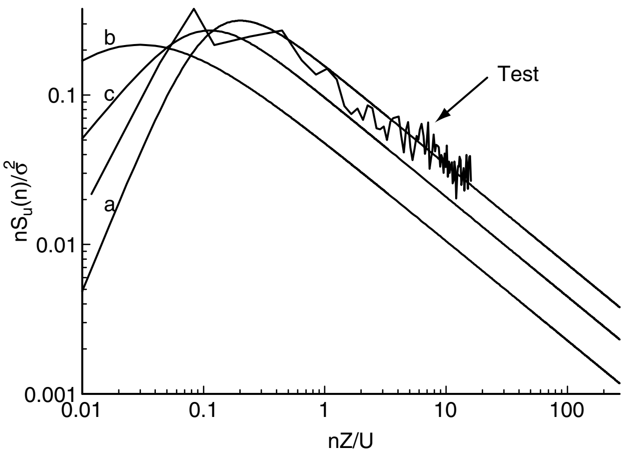


(a) Terrain category A

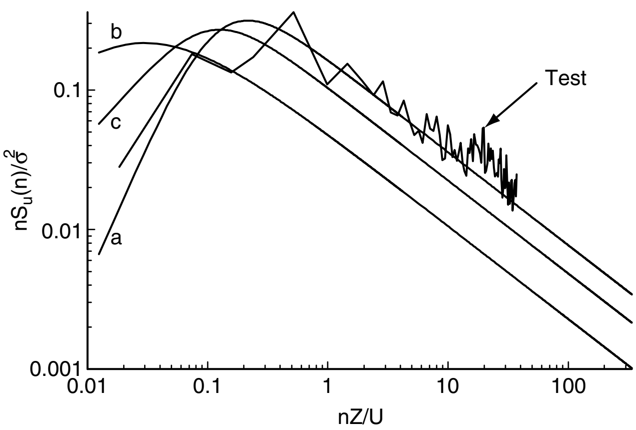


(b) Terrain category B

Figure 3. Profiles of mean velocity U and turbulence intensity I_u used in wind tunnel test



(a) Terrain category A



(b) Terrain category B

Figure 4. Power spectra at the height of the roof top in wind tunnel (a: Davenport spectrum; b: Karman spectrum; c: Kaimal spectrum)

non-dimensional net pressure coefficient *Cp* was determined by,

$$\text{Terrain category A}: C_{pi} = \frac{P_{i,u} - P_{i,b}}{(P_0 - P_\infty)\times\left(\dfrac{40}{150}\right)^{0.24}}$$

$$\text{B}: C_{pi} = \frac{P_{i,u} - P_{i,b}}{(P_0 - P_\infty)\times\left(\dfrac{40}{150}\right)^{0.32}} \tag{1a}$$

where C_{pi} is the pressure coefficient at the *i*th measuring point, $P_{i,u}$ is the upper pressure at the *i*th measuring point, and $P_{i,b}$ is the corresponding bottom pressure. P_∞ and P_0 are the static pressure and total pressure of the pitot tube at reference points in the test, respectively. Wind speed at the height of the roof top (40.0 m) was used to obtain the normalized pressure coefficient.

The non-dimensional pressure coefficient on the upper and bottom surfaces of the shed can be determined using a similar method,

$$\text{Terrain category A}: C_{pi,u} = \frac{P_{i,u}}{(P_0 - P_\infty)\times\left(\dfrac{40}{150}\right)^{0.24}} \tag{1b}$$

$$\text{B}: C_{pi,u} = \frac{P_{i,u}}{(P_0 - P_\infty)\times\left(\dfrac{40}{150}\right)^{0.32}}$$

$$\text{Terrain category A}: C_{pi,b} = \frac{P_{i,b}}{(P_0 - P_\infty) \times \left(\frac{40}{150}\right)^{0.24}} \tag{1c}$$

$$\text{B}: C_{pi,b} = \frac{P_{i,b}}{(P_0 - P_\infty) \times \left(\frac{40}{150}\right)^{0.32}}$$

3. METHOD FOR CALCULATING WIND-INDUCED DYNAMIC RESPONSE

The equation governing the motion of a structure under the action of turbulent wind can be written in a matrix style as,

$$[M]\{\ddot{y}\} + [C]\{\dot{y}\} + [K]\{y\} = [R]\{p(t)\} \tag{2}$$

where $[M]$, $[C]$, and $[K]$ are the mass, damping, and stiffness matrixes (n-by-n matrix), respectively. $\{y\},\{\dot{y}\}$, and $\{\ddot{y}\}$ are the displacement, velocity, and acceleration vectors of the structure, respectively. $[R]$ is the force indicating matrix (m-by-n matrix) composed of zeroes and ones, which expands the force vector $\{p(t)\}$ of m dimension into the vector of n dimension. Results of the simultaneous pressures from the wind tunnel test were used to obtain the wind loadings needed for calculating wind-induced responses based on the rule of similarity.

The power spectrum density (PSD) of the dynamic displacement (of the structure), which takes into account coupling effects between modes, based on random vibration theory and the hypothesis of classic damping, can be written as,

$$[S_{yy}(\omega)] = \sum_{j=1}^{n}\sum_{k=1}^{n} \left\{\phi_j\right\} H^*{}_j(i\omega) \left\{\phi_j\right\}^T [R] \\ [S_{pp}(\omega)][R]^T \left\{\phi_k\right\} H_k(i\omega) \left\{\phi_k\right\}^T \tag{3}$$

The root mean square (RMS) value of the structure wind-induced response when pressure spectra are double-sided can be determined by,

$$\sigma_y = \sqrt{2\int_0^\infty S_{yy}(\omega)\,d\omega} \tag{4}$$

where G is the "gust response factor", computed using the following equation,

$$G = \frac{\hat{R}_{Peak}}{\bar{R}} \tag{5}$$

where $\hat{R}_{Peak}$ is the peak response and $\bar{R}$ is the mean response. The gust response factor reflects dynamic amplification when structures are subjected to fluctuating wind loads. $\hat{R}_{Peak}$ is determined using,

$$\hat{R}_{Peak} = \bar{R} \pm g\sigma_R \tag{6}$$

where g is the peak factor, set as 2.5 here, and σ_R is the RMS value of a specific response. The "$\pm$" sign assures that the $\hat{R}_{Peak}$ obtained is the absolute maximum. Different values of peak factor were obtained when data from the wind tunnel test were analyzed. The values generally ranged from 2.5 to 4.0. Peak factors were uniformly set at 2.5 for simplicity, meaning the probability of exceeding a value above RMS is less than 0.62%.

4. RESULTS AND DISCUSSION

4.1. Mode Analysis of the Structure

The mode shapes of vibration are shown in Figure 5. The first natural frequency is 1.385 Hz, and about 30 mode shapes range from 1.385 to 5.511 Hz. The natural frequencies are found to be fairly close to one another. This is a very important consideration when analyzing the dynamic response of large-span roofs.

4.2. Computing Parameters

The wind and structural parameters for computation were as follows: (1) terrain category: A and B; (2) 10 minute averaged wind speed at 10 m height: 42.01 m/s (category A) and 35.77 m/s (category B); (3) structural damping ratio: 0.01; and (4) the number of mode participating in vibration was 50.

4.3. Characteristics of Wind-Induced Response under Interference Conditions

The analysis of the characteristics of the wind-induced responses of the shed for 18 cases conforms to the method and computing parameters mentioned above. Only the displacement response analyses were presented in this paper.

The wind-induced results between 180° and 270° direction are analyzed because of symmetry. An unfavorable wind direction can be found in each case (Table 1). Thus the wind direction probability associated with maximum peak responses can be evaluated based on these unfavorable directions (Figure 6). An oblique wind at 35°–45° to the span-wise direction is an unfavorable wind direction. Maximum probability (37.5%) of the worst results occurs when the flow attacks at the 210° wind direction in the case of the upstream interfering shed.

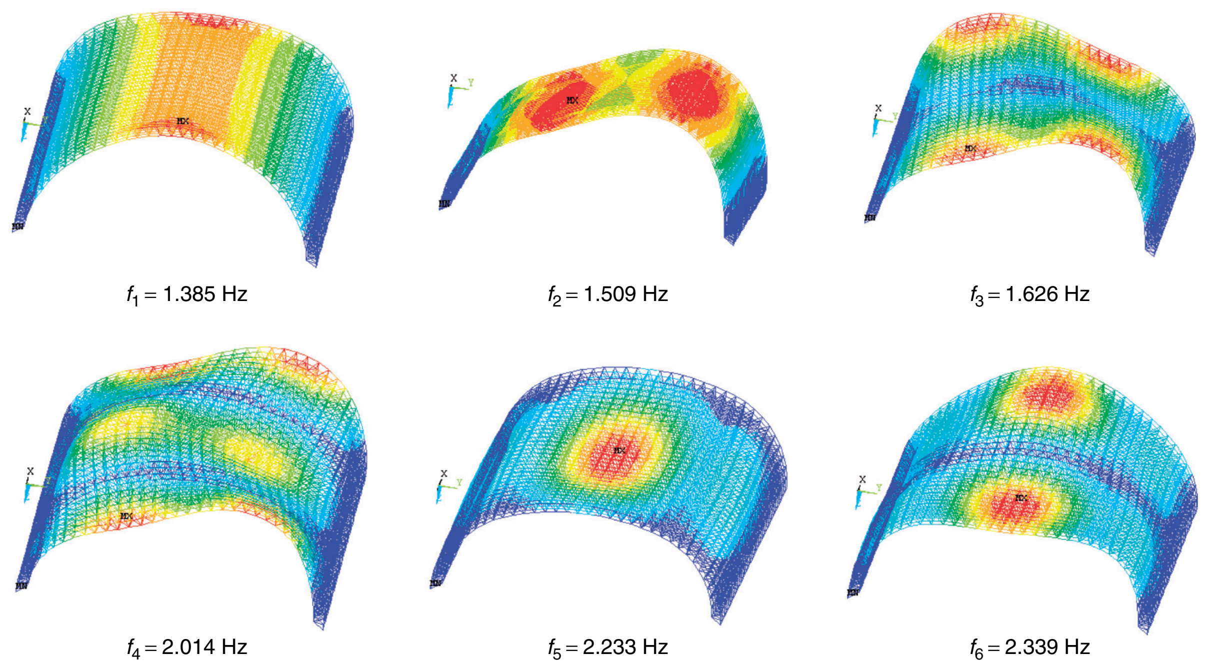


Figure 5. Vibration modes of shed

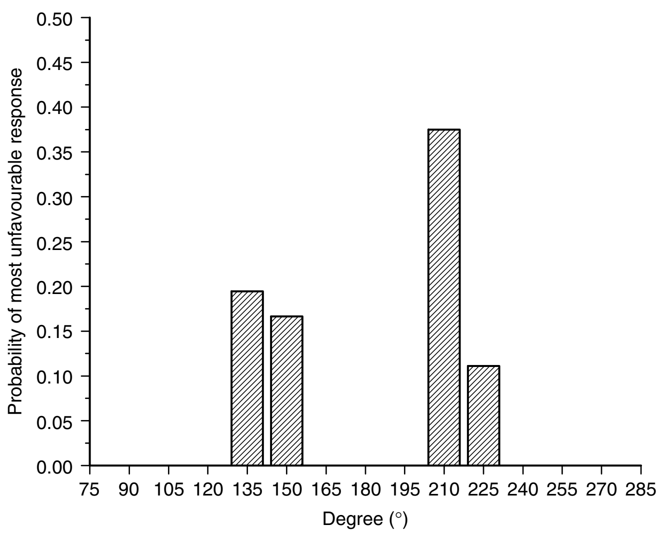


Figure 6. Most unfavorable wind directions

Absolute maximum values of vertical and span-wise peak responses appear when an oblique wind blows at the 135° direction with no interfering shed nearby, but when there is low coal stack inside.

Gust response factors for the maximum vertical/span-wise peak response at all wind directions in the 18 cases are plotted in Figure 7. There are two gust response factors for each case, corresponding to the vertical and span-wise peak responses. Figure 7 shows that the gust response factors for terrain category A are generally a little higher than those for terrain category B (cases 1–9 are in terrain category A, while cases 10–18 are in terrain category B). The gust response factors of the vertical response are higher than those of the span-wise peak response. Gust response factors of the maximum peak response in terrain category A range from 1.47 to 1.65, while those in terrain category B fall within 1.36 and 1.48. The values in Figure 7 may relate to different wind directions because each gust response factor corresponds to a particular case. The values of gust response factors of the vertical and span-wise responses in the worst cases (at 135° wind direction in the eighth case, terrain category A, isolated shed, low stack) are 1.53 and 1.48, respectively.

Vertical displacements at node A and span-wise displacements at node B are located at the mid- and 1/4 mid-spans, respectively (Figure 1). This paper analyzes the data in terrain category A only (without loss of generality) because the results in this category are similar to those in terrain category B to a large extent. Focus is directed only on two typical wind directions. One is the 135° wind direction where peak responses are the highest when the principal shed is on the windward side, the other is the 270° wind direction when the principal shed is on the leeward side. Figures 8 and 9 show the mean, root mean square, background and resonant responses at Nodes A and B under 135° and 270° wind directions in the nine cases (terrain category A). Figure 8 shows that mean responses are dominant when the interfering shed is on the leeward side (135° wind direction). These mean responses are almost five times as large as the root mean square responses. Figure 8 also shows that the background component contributes more than the resonant component. On the one hand, the

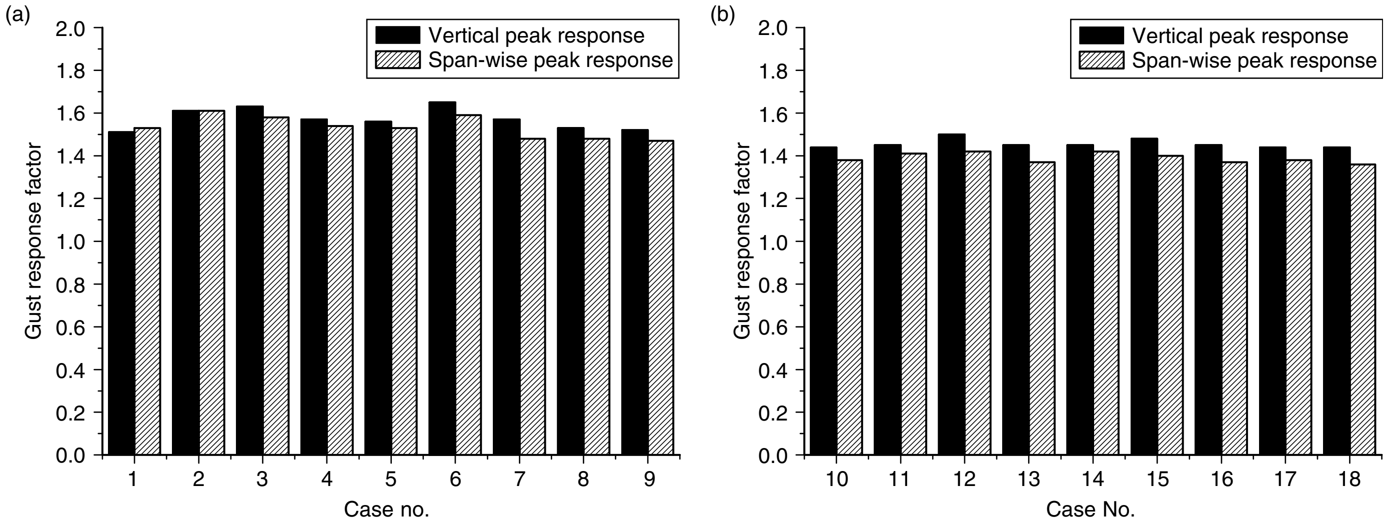


Figure 7. Gust response factor for maximum peak response

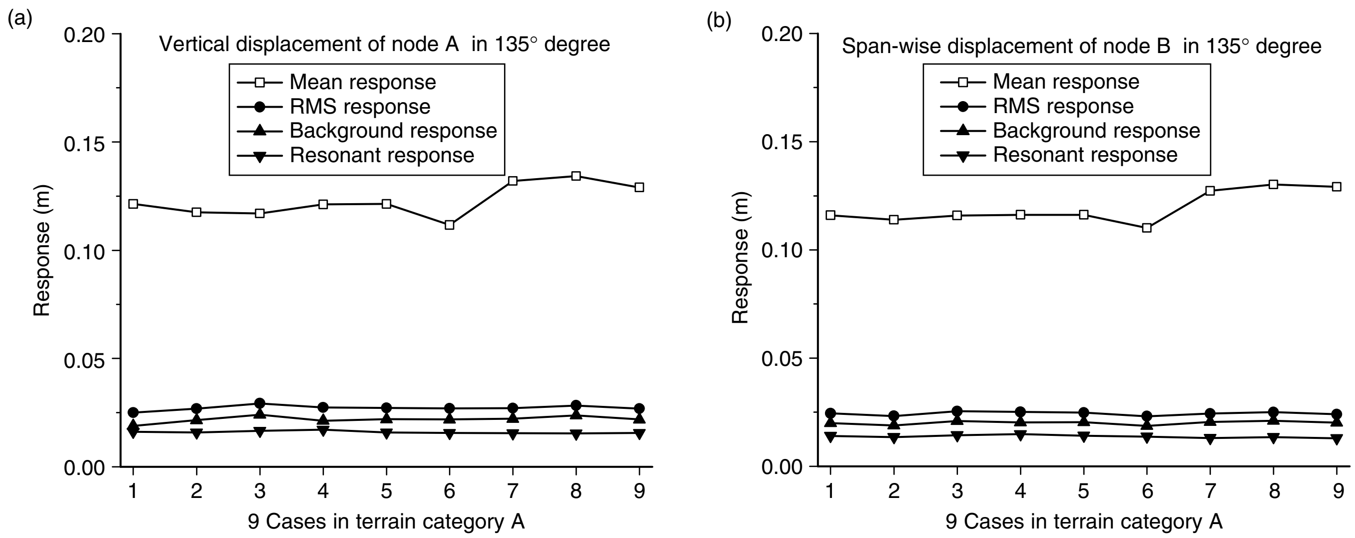


Figure 8. Mean, RMS, background and resonant responses of node A&B at 135° wind direction

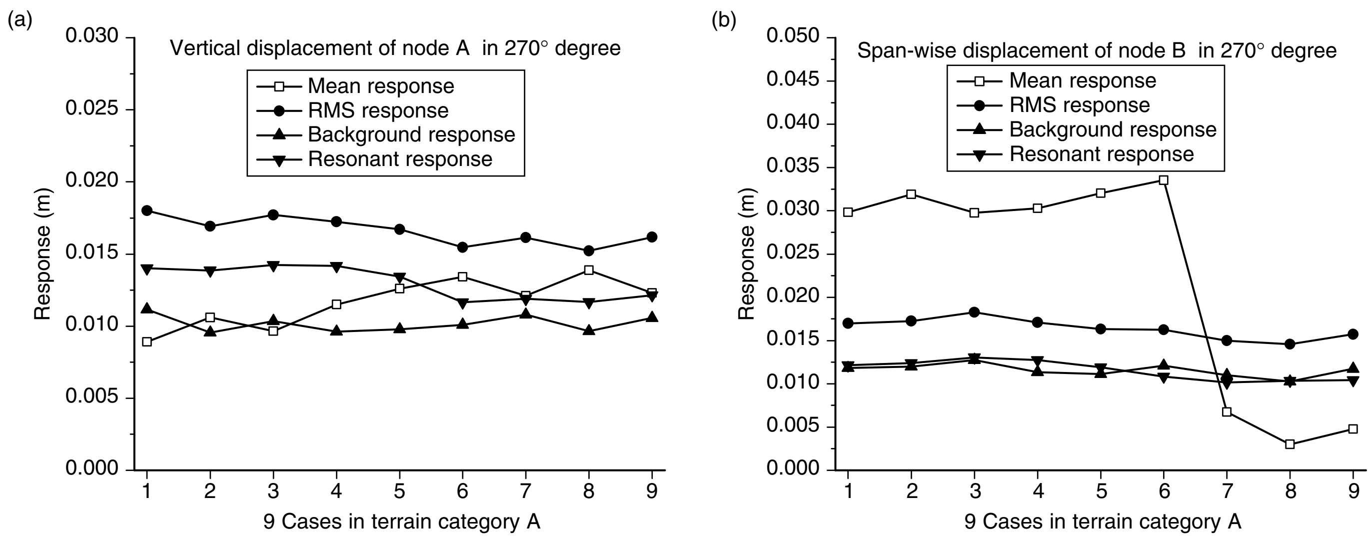


Figure 9. Mean, RMS, background and resonant responses of node A&B at 270° wind direction

situation is somewhat more complicated than that on the leeward side when the interfering shed is on the windward side (270° wind direction). Figure 9(a) shows that the value of the mean vertical displacement at node A is 44.4–86.5% of the root mean square response due to interference effects. However, the presence of the interfering shed causes the span-wise response to represent different characteristics. Figure 9(b) shows that mean span-wise responses are also dominant. These are almost 2.4 times the root mean square responses when the interfering shed exists (cases 1–6) while the fluctuating component contributes more than the mean component when there is no interfering shed.

4.4. Analysis of Interference Factor

This section emphasizes the interference effects on peak responses following the analysis of the interference factor (IF) because peak responses are very important in structural design. IF is calculated as shown below:

$$\text{IF} = \frac{\text{Maximum peak response of a shed under interference condition}}{\text{Maximum peak response of an isolated shed}} \tag{7}$$

where maximum peak response in the numerator could be the vertical or span-wise peak response of a node for a certain wind direction and certain interference condition and the denominator represents the peak response of the same node in an isolated situation. Obviously, IF reflects the interference effects. Responses in the numerator and denominator are obtained for the same node at a certain wind direction and certain interference condition. However, such node could be different in different wind directions because the maximum peak response could occur in different nodes when the wind comes from different directions.

4.4.1. Interference factor of vertical peak displacement

Figure 10 shows how the interference factor for peak vertical displacement varies as a function of wind direction. The presence of an interfering shed is also shown to have more influence on the wind-induced responses of the structure than the presence of coal stacks inside. This leads to similar variations in the interference factor for different terrain categories [Figures 10(a), (b)]. Figures 10(a) and 10(b) are illustrated for clarity of presentation.

The interference pattern [Figures 10(a) and (b)] becomes quite complex with the inclusion of another shed in the vicinity. In most cases, when the principal shed is on the windward side (wind direction is 90° –165°), peak vertical displacements are reduced

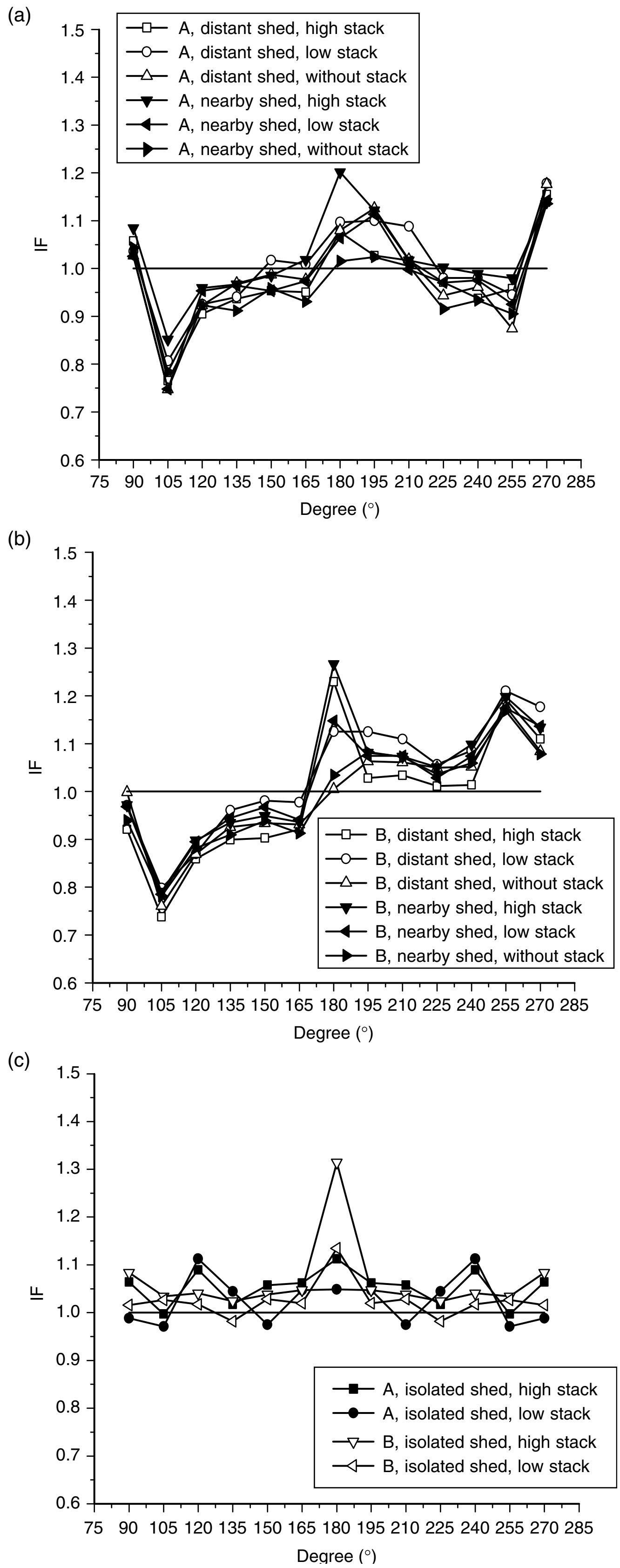


Figure 10. Interference factor of peak vertical displacement as a function of wind direction

(IF<1.0) under interference conditions, except for the 90° wind direction in terrain category A. The minimum IF (0.738) is found when an oblique wind blows at 15° to the span-wise direction (105° wind direction, terrain category B, distant shed, high stack). Interference factors are higher than 1.0 (isolated shed case) when the flow is parallel to the longitudinal direction of the roof (180° wind direction). The maximum IF occurs in case 13 (terrain category B, nearby shed, high stack), where an IF of 1.267 implies an increase of 26.7%. The high stack inside is the main reason for the higher IF values (Section 4). According to previous studies, absolute peak responses are not high, although higher values of IF appear. Interference effects also decrease quickly in most cases when the flow is not parallel to the longitudinal direction. Third, there are some differences between terrain categories A and B when the principal shed is on the leeward side (wind direction is 195°–270°). IF values for terrain category B are higher than 1.0 while IF values less than 1.0 are obtained for the wind directions 225°–255° for terrain category A.

Figure 10(c) shows that when interference comes only from the coal stack inside, the interference factors in most cases are larger than 1.0. This indicates that the coal stacks can increase vertical peak responses. IF reaches a maximum value of 1.314 for terrain category B (isolated shed, high stack) when the wind is parallel to the longitudinal direction of the roof (180° wind direction), coinciding with the maximum IF in Figures 10(a) and (b). IF is 1.044 when the wind direction is 135° and the maximum absolute value of the vertical peak response occurs in the eighth case. This means there is a little magnification for the vertical peak responses.

4.4.2. Interference factor of span-wise peak displacement

The variation of IF of the peak span-wise displacement with wind direction is presented in Figure 11. The curves of the span-wise displacement are significantly different from those of the vertical responses, comparing Figures 10 and 11. Figure 11, as for Figure 10, reflects the fact that the adjacent shed has more influence on the wind-induced responses of the structure than the coal stacks inside.

Figures 11(a) and (b) also present certain observations. Firstly, peak span-wise displacements are reduced (IF < 1.0) in most cases (except at 90° wind direction in terrain category B), when the principal shed is on the windward side (with the range of wind direction is from 90°–165°). This is similar to that seen in Figure 10. The minimum IF (0.663) is found when an oblique wind blows at 15° to the span-wise direction (105° wind direction, terrain category B, distant shed, high stack), and the peak response is 33.7% smaller than that of an isolated shed. Secondly, interference factors are generally around 1.0 when the flow is parallel to the longitudinal direction of the roof

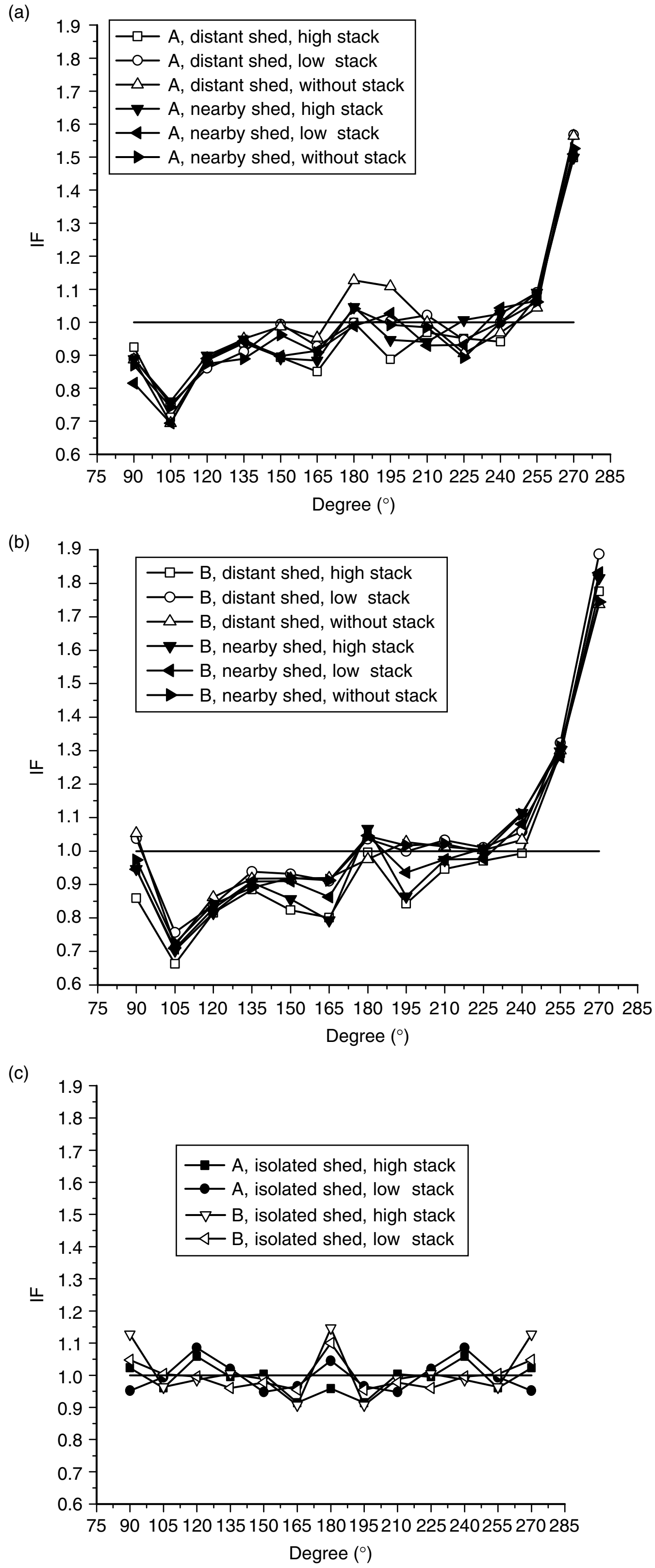


Figure 11. Interference factor of peak span-wise displacement as a function of wind direction

(180° wind direction). These are smaller than the values of the vertical responses. Maximum IF (1.127) occurs in the 3rd case (terrain category A, distant shed, without stack). Thirdly, IF values in most cases are less than 1.0 when the principal shed is on the leeward side (the range of wind direction is 195°–240°), while the value of IF increases with increase of wind direction (240°–270°). A sharp increase is observed especially for a 270° wind direction. The maximum IF values in terrain categories A and B are 1.568 and 1.877, respectively. These are found in the case of a distant shed and low stacks, indicating 56.8% and 87.7% increases. Along-wind forces on a downstream building, are generally reduced due to the shielding by upstream buildings. However, this paper shows that the upstream shed produces adverse effects on a downstream one, mainly caused by the different pressure on the bottom surface (Section 4). The absolute value of the response is not the most unfavorable case despite the significant increase in peak responses of the downstream shed. Obvious shielding effects are also observed in Figures 10(a) and (b) and Figures 11 (a) and (b), although enhancement is also found.

Figure 11(c) shows that when only the coal stacks cause interference, more than half of the interference factors are less than 1.0, indicating that coal stacks decrease span-wise peak responses in most cases, different from the vertical response results. The interference factor reaches a maximum value (1.147, terrain category B, isolated shed, high stack) when the wind is parallel to the longitudinal direction of the roof (at 180° wind direction), similar to Figure 10(c). The interference factor is 1.020 when the wind direction is 135°, when the maximum absolute value of span-wise peak response occurs in terrain category A, indicating interference effects are insignificant. Interference only increases vertical and span-wise peak response by a little in the worst cases. Interference effects from the coal stacks inside are small and even become negligible (except for the situation of an angle of attack of 180°) when seen together with the observations in Figure 10(c).

5. INTERFERENCE MECHANISM IN SOME SPECIFIC CASES

Since the emphasis of this paper is upon wind-induced responses, detailed characteristics of wind pressure on the roof surface of shed are not given. Interference mechanisms in specific cases, however, are nevertheless explored and wind pressure distributions on the surface of the shed are analyzed.

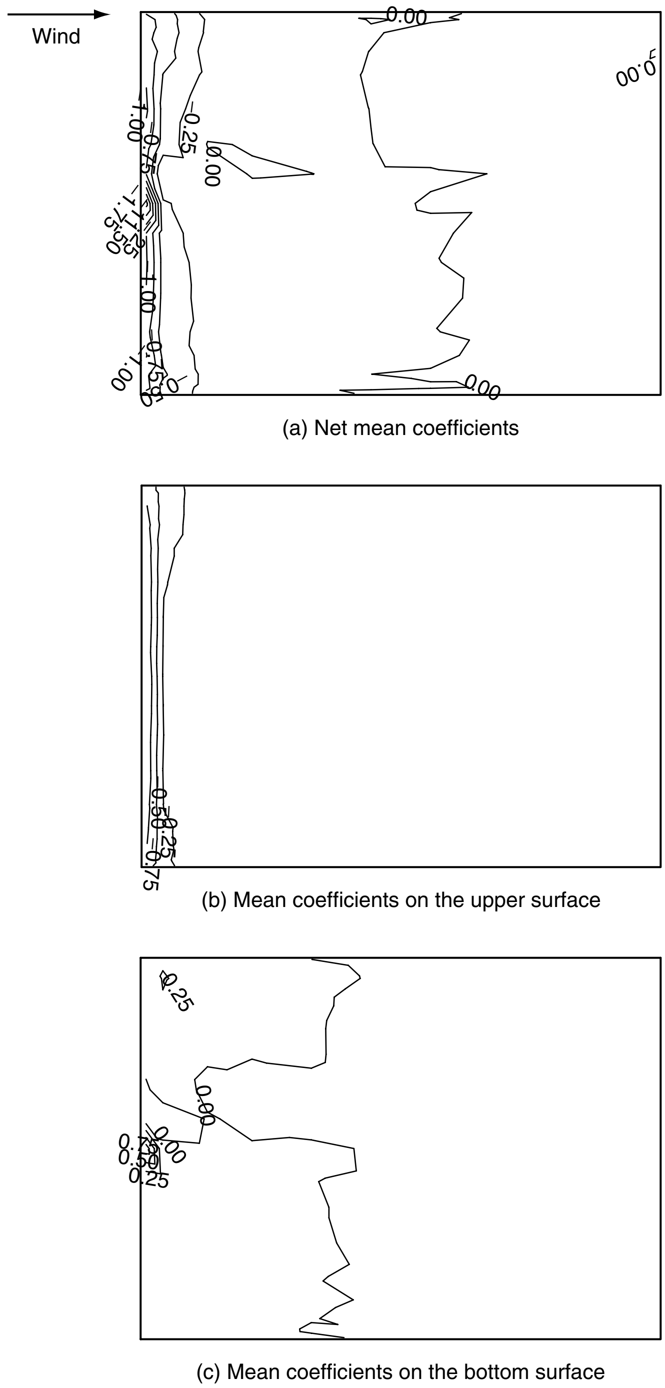


Figure 12. Contours of mean pressure coefficients (180° wind direction, terrain category B, isolated shed, without stack)

Peak responses were mainly determined by static wind pressure distributions because mean responses play the most important role in the design. Figures 12 to 14 show the contours of the mean pressure coefficients on the roof surface at a wind direction of 180° under non-interference and the two types of interference conditions.

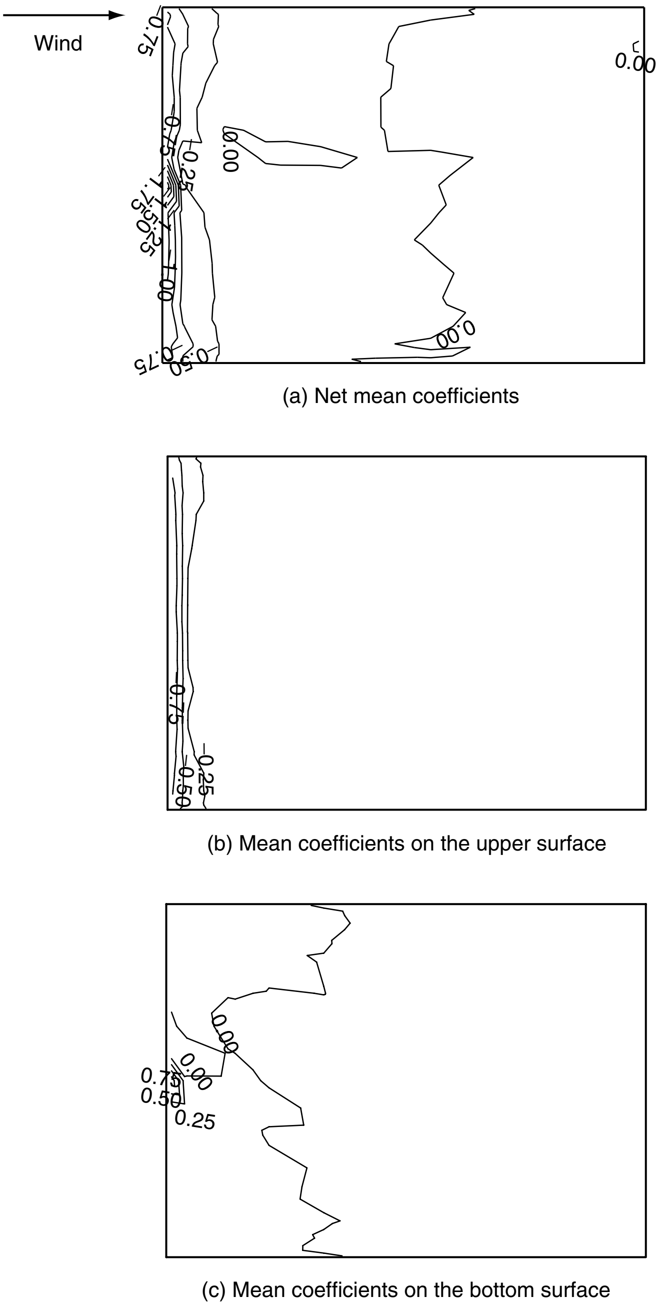


Figure 13. Contours of mean pressure coefficients (180º wind direction, terrain category B, nearby shed, without stack)

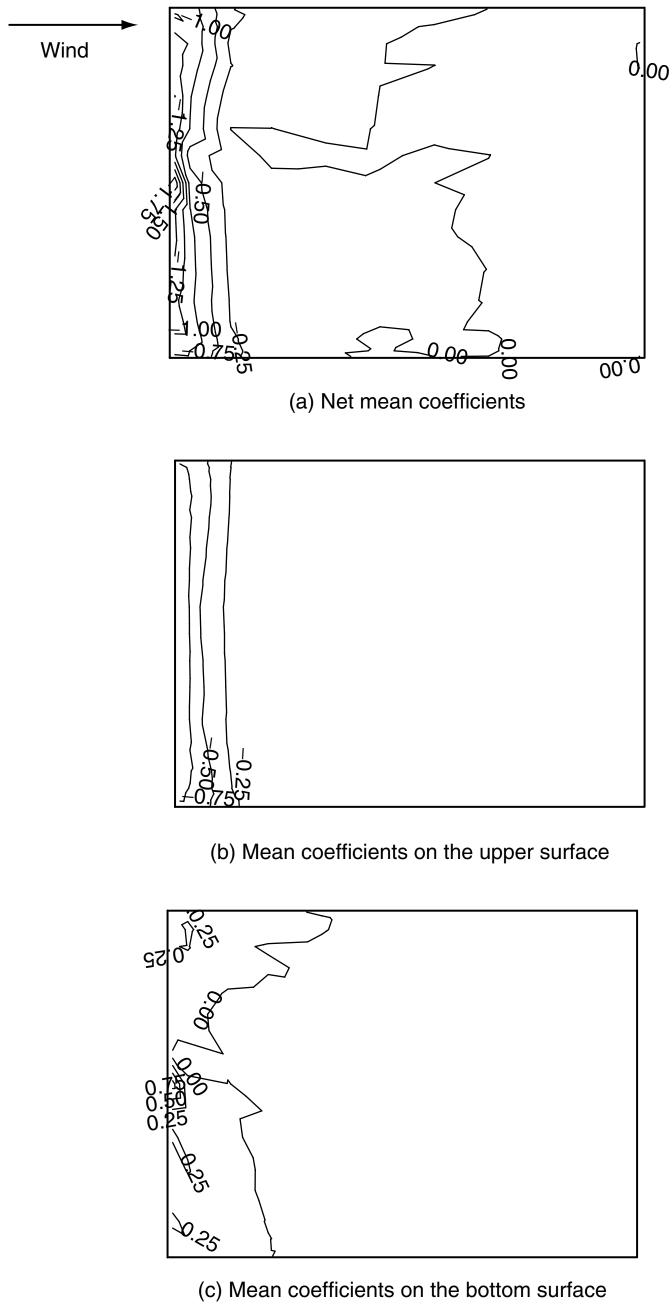


Figure 14. Contours of mean pressure coefficients (180º wind direction, terrain category B, nearby shed, high stack)

Almost similar pressure distributions are found on the upper surface for the three conditions above. The wind can blow straight across the shed when the flow is parallel to the longitudinal direction of the roof because there are no side walls. Therefore, the existence of a nearby shed has little impact on the principal shed if the pressure coefficients on the upper surface of the isolated shed are compared with those of the sheds with a nearby shed. On the other hand, coal stacks do increase positive pressure in the end area of the windward region on the bottom surface. This leads to a larger negative net pressure in those areas. The effects of these enlarged negative pressures augment vertical displacement and are the reasons why larger vertical displacement interference factors occur when high coal stacks exist at the 180° wind direction.

The largest span-wise displacement interference factors are found at a 270° wind direction. The contours of mean pressure coefficients on the roof surface at a 270° wind direction under non-interference and interference conditions are shown in Figures 15 to 17 in order to explain why along-wind

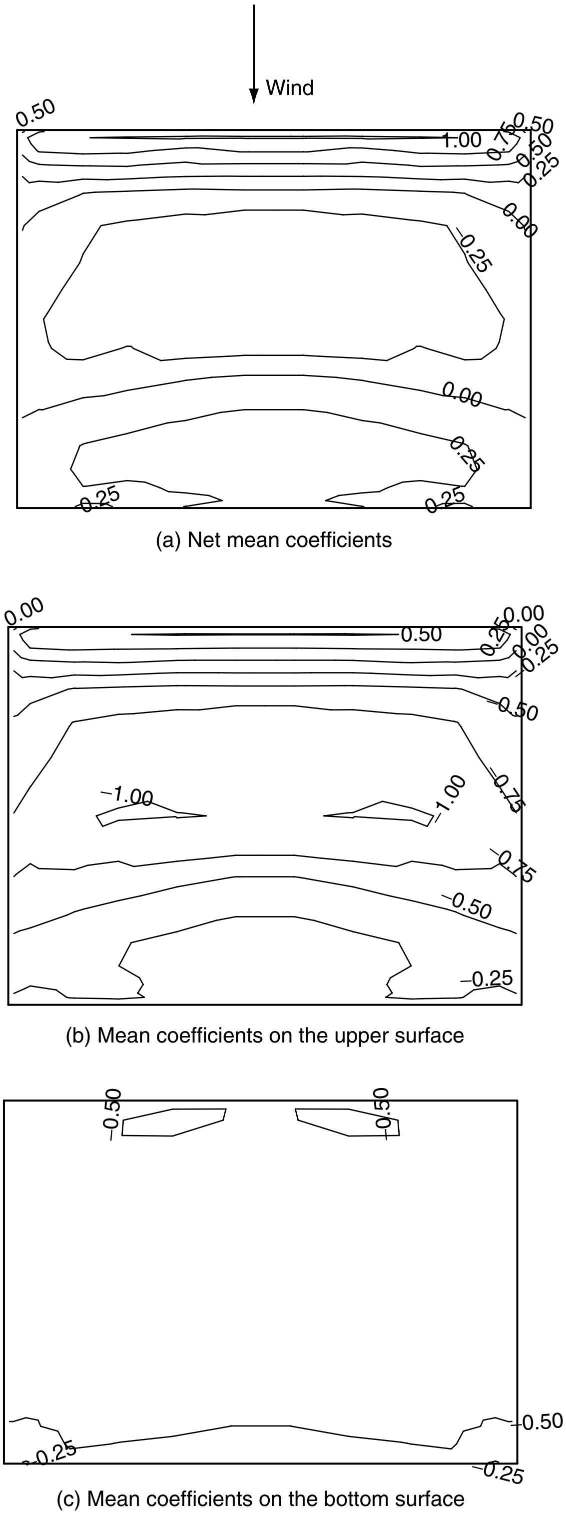


Figure 15. Contours of mean pressure coefficients
(270º wind direction, terrain category B, isolated shed, without stack)

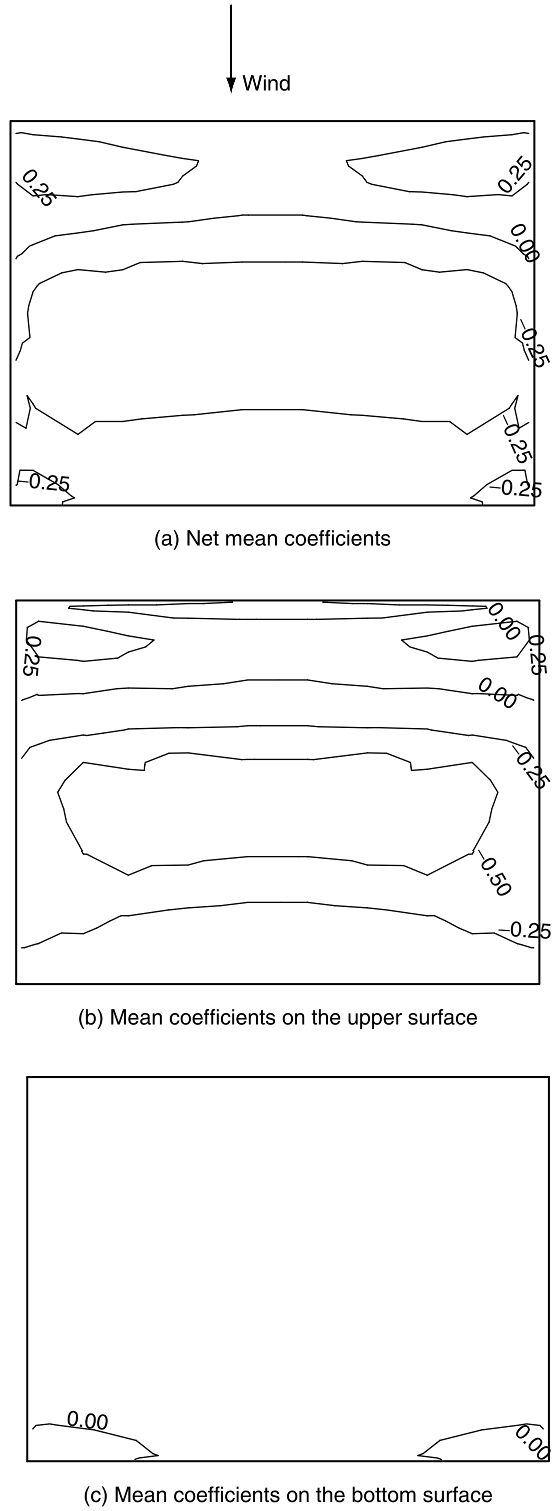
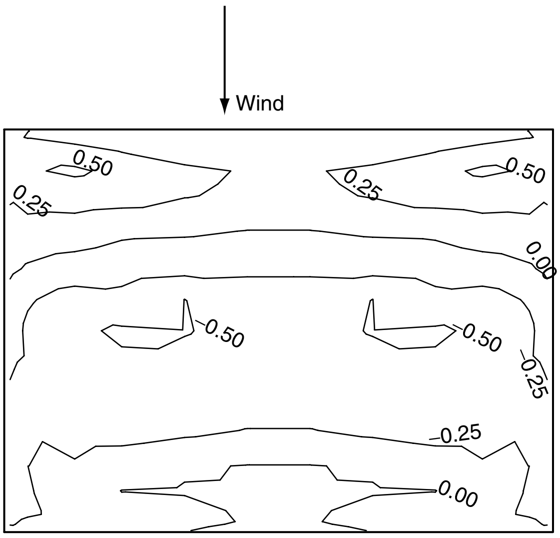
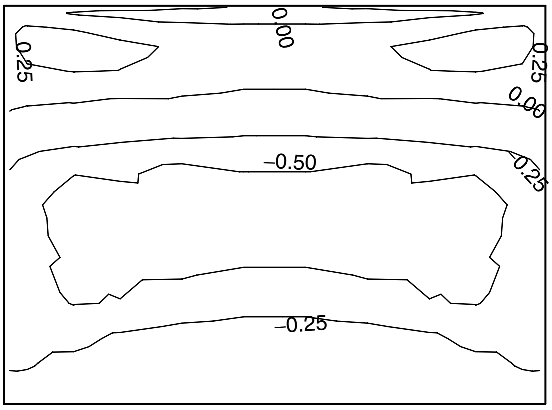


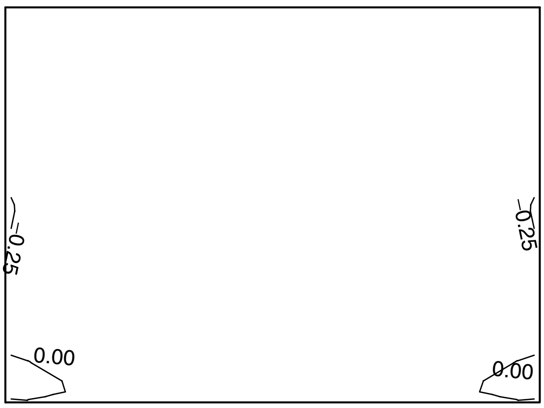
Figure 16. Contours of mean pressure coefficients
(270º wind direction, terrain category B, nearby shed, without stack)



(a) Net mean coefficients



(b) Mean coefficients on the upper surface



(c) Mean coefficients on the bottom surface

Figure 17. Contours of mean pressure coefficients (270º wind direction, terrain category B, nearby shed, high stack)

responses of the principal shed increase when shielded by upstream buildings. The absolute values of pressure on the roof top in the windward region are greatly reduced by the shielding effects of a nearby shed. Pressures on the upper surface in the leeward region remain almost the same. Pressures on the bottom surface are very small when a nearby shed exists, indicating that the inside stack has little effect on the bottom surface. However, obvious negative pressures on the bottom surface are found in the isolated shed condition. Pressures on the bottom surface then change the net pressure distributions. The direction of the resultant wind force on the windward side of the principal shed is opposite to that on the leeward side when the shed is isolated. The wind forces on both windward and leeward sides act parallel to the wind approach direction when there is an interfering shed. This is the reason why interference factors are significantly higher than 1.0 for a 270° wind direction regardless of the existence of upstream buildings.

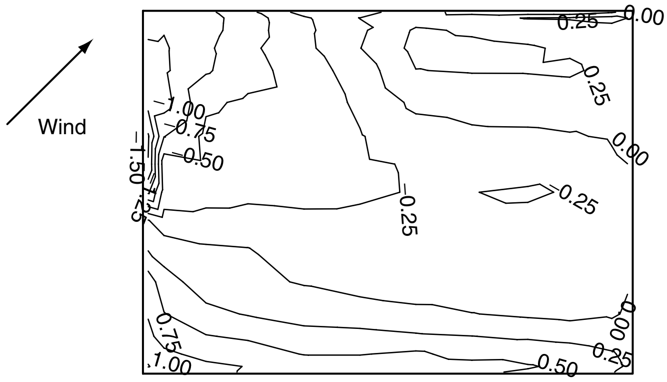


Figure 18. Contours of net mean pressure coefficients (135º wind direction, terrain category B, nearby shed, without stack)

Figure 18 gives the contours of the net mean pressure coefficients for a 135° wind direction when there is a nearby shed but no stack. Net wind pressures are higher than those with the wind parallel to the span-wise direction of the roof, when an oblique wind blows at 35°– 45° to the span-wise or longitudinal directions. Pressure distributions with an oblique wind attack are unsymmetrical. The absolute values of the net pressures on the surface are not small when the flow is parallel to the longitudinal direction of the roof (180° wind direction). But because pressure distributions in this situation are almost symmetrical, they cannot produce large responses. An oblique wind, however, generally induces large responses. Figure 19 presents the contours of the net RMS pressure coefficients for 135°, 180°, and 270° wind directions with a nearby shed but no stack. Pressures on the surface for 270° wind directions are obviously smaller than those for other wind directions. Thus only small responses occur when the flow is parallel to the span-wise direction of the shed.

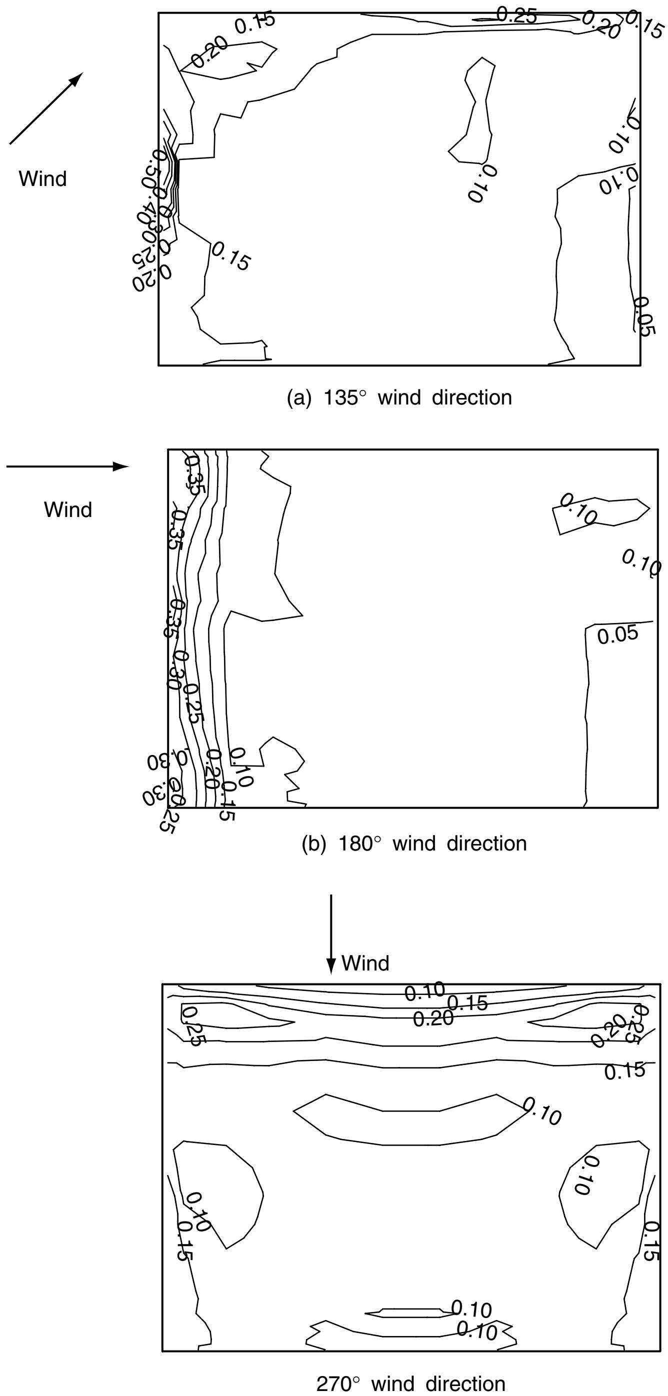


Figure 19. Contours of net RMS pressure coefficients (terrain category B, nearby shed, without stack)

6. CONCLUSIONS

The interference effects caused by a nearby shed and the presence of a stored coal stack, on the wind-induced responses of a dry coal shed have been studied. The main results consist of:

(1) The neighboring shed has more influence on the wind pressure distribution than the coal stack inside. Main interference parameters affecting the principal shed are the adjacent building, the incident wind direction, the terrain category, and the spacing of adjacent sheds and the coal stacks inside. The adjacent shed and incident wind direction parameters are more influential than the spacing of the adjacent sheds and coal stacks inside.

(2) The most unfavorable results occur with an oblique wind blowing at 45° to the span-wise direction when there is no interfering nearby shed and there is a low coal stack inside. Gust response factors in terrain category A are generally higher than those in terrain category B, while gust response factors of vertical responses are higher than those of span-wise peak responses. Mean responses are dominant and the background component contributes more than the resonant component in most cases.

(3) The interference factor reaches maximum value for vertical peak responses (maximum value is 1.314) when the wind is parallel to the longitudinal direction of the roof. IF reaches a maximum value for span-wise peak responses (maximum value is 1,877) when the principal shed is located downstream and the flow is parallel to the span-wise direction of the roof (270° wind direction). This is mainly caused by different pressure distributions on the bottom surface. Absolute values of the responses in the situations above are not the worst among all cases, although the shed does suffer significant increases in peak responses.

(4) Minimum interference factors of 0.738 and 0.663 for vertical and span-wise responses, respectively, are found when an oblique wind blows at 15° to the span-wise direction.

(5) The IF values are slightly higher than 1.0 for the maximum absolute value of the vertical and span-wise peak responses in all cases. Interference conditions therefore magnify the peak responses of an isolated roof only minimally.

ACKNOWLEDGEMENTS

This project is jointly supported by the Ministry of Science and Technology of China (Grant No. SLDRCE08-A-03), National Natural Science Foundation (50608060, 50621062) and National Science and Technology R&D Program of China (2006BAJ06B05), which are gratefully acknowledged.

REFERENCES

Ahmad, S. and Kumar, K. (2001). "Interference effects on wind loads on low-rise hip roof buildings", *Engineering Structures*, Vol. 23, No. 12, pp. 1577–1589.

Bailey, P.A. and Kwok, K.C.S. (1985). "Interference excitation of twin tall buildings", *Journal of Wind Engineering and Industrial Aerodynamics*, Vol. 21, No. 3, pp. 323–338.

Blessman, J. and Riera, J.D. (1979). "Interaction effects in neighbouring tall buildings", *Proceedings of the 5th International Conference on Wind Engineering*, Colorado State University, Fort Collins, CO, pp. 381–395.

GB5009-2001 (2006). *Load Code for the Design of Building Structures*, China Architecture and Building Press, Beijing, China. (in Chinese)

Gu, M., Xie, Z.N. and Huang, P. (2005). "Along-wind dynamic interference effects of tall buildings", *Advances in Structural Engineering*, Vol. 8, No. 6, pp. 623–635.

Ho, T.C.E., Surry, D. and Davenport, A.G. (1991). "The variability of low-buildings wind loads due to surroundings", *Journal of Wind Engineering and Industrial Aerodynamics*, Vol. 38, No. 2–3, pp. 297–310.

Huang, P. and Gu, M. (2005). "Experimental study on wind-induced dynamic interference effects between two tall buildings", *Wind and Structures*, Vol. 8, No. 3, pp. 147–161.

Hussain, M. and Lee, B.E. (1980). "A wind tunnel study of the mean pressure forces acting on a large group of low-rise buildings", *Journal of Wind Engineering and Industrial Aerodynamics*, Vol. 6, No. 3–4, pp. 207–225.

Khanduri, A.C., Stathopoulos, T. and Bédard, C. (1998). "Wind-induced interference effects on buildings - a review of the state-of-the-art", *Engineering Structures*, Vol. 20, No. 7, pp. 617–630.

Lam, K.M., Leung, M.Y.H. and Zhao, J.G. (2008). "Interference effects on wind loading of a row of closely spaced tall buildings", *Journal of Wind Engineering and Industrial Aerodynamics*, Vol. 96, No. 5, pp. 562–583.

Saunders, J.W. and Melbourne, W.H. (1979). "Buffeting effects of upwind buildings", *Proceedings of the 5th International Conference on Wind Engineering*, Colorado State University, Fort Collins, CO, pp. 593–605.

Stathopoulos, T. (1984). "Adverse wind load on low building due to buffeting", *Journal of Structural Engineering,* ASCE, Vol. 110, No. 10, pp. 2374–2392.

Taniike, Y. (1992). "Interference mechanism for enhanced wind forces on neighbouring tall buildings", *Journal of Wind Engineering and Industrial Aerodynamics*, Vol. 42, No. 1–3, pp. 1073–1083.

Tsutsumi, J., Katayania, T. and Nishida, M. (1992). "Wind tunnel tests of wind pressure on regular aligned buildings", *Journal of Wind Engineering and Industrial Aerodynamics*, Vol. 43, No. 1–3, pp. 1799–1810.

Xie, Z.N. and Gu, M. (2007). "Simplified formulas for evaluation of wind-induced interference effects among three tall buildings", *Wind and Structures*, Vol. 95, No. 1, pp. 31–52.

Zhang, W.J., Kwok, K.C.S. and Xu, Y.L. (1994). "Aeroelastic torsional behaviour of tall buildings in wakes", *Journal of Wind Engineering and Industrial Aerodynamics*, Vol. 51, No. 2, pp. 229–248.