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Wind tunnel modeling of flow over mountainous valley terrain

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Abstract. Wind tunnel experiments were conducted to investigate the wind characteristics in the mountainous valley terrain with 4 simplified valley models and a 1:500 scale model of an existing valley terrain in the simulated atmospheric neutral boundary layer model. Measurements were focused on the mean wind flow and longitudinal turbulence intensity. The relationship between hillside slopes and the velocity speed-up effect were studied. By comparing the preliminary results obtained from the simplified valley model tests and the existing terrain model test, some fundamental information was obtained. The measured results indicate that it is inappropriate to describe the mean wind velocity profiles by a power law using the same roughness exponent along the span wise direction in the mountainous valley terrain. The speed-up effect and the significant change in wind direction of the mean flow were observed, which provide the information necessary for determining the design wind speed such as for a long-span bridge across the valley. The longitudinal turbulence intensity near the ground level is reduced due to the speed-up effect of the valley terrain. However, the local topographic features of a more complicated valley terrain may cause significant perturbation to the general wind field characteristics in the valley.

Keywords: mountainous valley terrain; wind tunnel test; speed-up effect.

1. Introduction

Neutral atmospheric flows are perturbed greatly by the presence of local topographic feature such as hills and valleys. Wind field characteristics in complex terrain contain complicated flow phenomena among which mean wind "speed-up" and the variation of turbulence flow structure occur. Speed-up effects describe the increase of wind speed above a hill surface as compared with the wind over a flat surface at the same height above the surface, and it is generally defined by a fractional speed-up ratio Δs, which is expressed as

$$\Delta s = \frac{U(z) - U_0(z)}{U_0(z)} \quad (1)$$

where $U(z)$ is the velocity at height z above the local hill surface, and $U_0(z)$ is an undisturbed reference

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velocity at the same height above the local ground. As an accurate prediction of wind field characteristics in complex terrain plays a critical role in a wide range of wind-related subjects, such as extraction of wind energy, wind load on structures and pollutant dispersion, extensive work has been done in the past decades in order to understand the wind field characteristics in a complex terrain.

Previously researchers have addressed the theory and modeling of flow over complex terrain by two-dimensional models (Taylor and Gent 1974, Jackson and Hunt 1975). Following those initial two-dimensional models, numerous studies have been done to extend simulation models to three-dimensional situation and apply them to the full-scale terrain. For example, Mason and Sykes (1979) studied the flow over an isolated hill of moderate slope and extended the 2D Jackson - Hunt model to 3D situation. Then, a number of field measurements of flow over isolated hill have been made by Mason and Sykes (1979) and Holmes, *et al.* (1979). Taylor and Welmsley together with their group members developed the series of MS3DJH models and introduced some guidelines for the prediction of flow over hills (e.g., Taylor, *et al.* 1983, Taylor and Lee 1984, Taylor 1998, Walmsley, *et al*. 1982, 1986). Based on simulation results obtained by the MS3DJH model and wind tunnel studies, another simple model hereafter referred as LSD model was proposed by Lemelin, *et al*. (1988). This model introduced explicit formulations to estimate the speed-up effect at any position above the hillside as well as above the hilltop. In addition, lots of experimental studies and field measurements have been done to improve our understanding of the flow over complex terrain. Reviews of relevant research work in the early stage were covered by Taylor, *et al*. (1987) and Finnigan (1988). Recently, researchers have concentrated more attention on the situation of flow over more complex terrain and steeper hills which may cause flow separation rather than isolated and idealized terrain models, for example, (Carpenter and Locke 1999, Duijm 1996, Ishihara, *et al*. 1999, Kim, *et al*. 1997, Lubitz and White 2007, Miller and Davenport 1998, Yamaguchi, *et al*. 2003). These previous studies have greatly improved our understanding of the wind flow over complex terrain.

Most of the above mentioned studies concentrated on the turbulent flow over complex terrain were to study the wind speed-up effect in order to find the appropriate site for wind energy extraction facilities or to determine an accurate design wind speed for structures in the near surface regions, and other studies mainly focused on spatial distributions of wind characteristics in complex terrain for the purpose of reducing pollutant dispersion in the atmosphere. However, when it comes to the situation of a long-span bridge across the wide and deep valley in a mountainous terrain, both the speed-up effect on the hilltop which may mainly account for the wind load on the bridge tower and the wind characteristics distribution in the valley, especially at the height of the designed bridge deck, may become important for the determination of design wind speed. But few relevant studies could be found in the literature. Also, as there are usually few weather stations in such mountainous area, the available meteorological data are scarce. So in such circumstances, the influence of topographic features on the determination of design wind speed of structure remains ambiguous. In some codes of practice, wind tunnel tests of the real terrain model are normally suggested. Although the real terrain model tests can reflect detailed information of a particular terrain, it is difficult to obtain more fundamental information due to the high geographic sensitivity of the flow structure.

The main objective of this study is to gain understanding of the impact of mountainous valley terrain on the wind field characteristics in the valley and its further application to determine the design wind speed for structures within the valley such as for long-span bridges. In practice, one of the effective methods to obtain more fundamental information about the impact on flow imposed by the terrain geometry is to compare the results of real terrain model tests with that of the representative simplified model tests. So in the present study, four simplified valley models with the same configuration but different hill side slopes together with one real valley terrain model were investigated in the simulated atmospheric boundary layer. Measurements of mean flow and turbulence intensity components were made and the influences of the hill surface roughness on the speed-up effect in the valley were also studied.

2. Simplified models test

2.1. Facility and valley models

The simplified models tests were conducted in an open-circuit wind tunnel, in the University of Adelaide, Australia, which has a working section of 0.5 m by 0.5 m and 2.1 m long and the free-stream wind speed ranged from 0 to 11 m/s. While the wind tunnel working section is relatively small and short, every effort was made with triangular spires and trip board to produce a reasonable approaching wind profile for testing. Also, the results of these simplified model tests were measured to compare with those obtained from the real terrain model tests. Without further validations with full scale data, some caution should be taken when applying these results to other design scenarios.

As the local topographic features of the real valley vary greatly, for the purpose of simplification, a generalized valley shape was made by two pieces of half conical hills which have the same slopes. The half conical hills were made by splitting a whole cone symmetrically, and each half of the conical hill was arranged at each side of the centre line of the wind tunnel working section with the hill surface facing each other. The cutting plane of the half cone formed a 45 degree angle with the vertical plane along the centre line of the wind tunnel to study the influence of flow separation which occurs when wind encounters the mountainous terrain. Then, two pieces of the half conical hills with the same slope composed one valley model. Altogether, four valley models with different hill side slopes were made. The base radius r of the conical hill was fixed at 14.3 cm, while the hill heights were 5.72 cm, 7.15 cm, 8.8 cm and 10.8 cm for the four models generating slopes of 0.4, 0.5, 0.615 and 0.755 respectively. The conical hills were made of 3 mm thick plywood yielding 3 mm high contour lines. The conical hill shape was defined by Eq. (2).

$$
\begin{aligned}
Z &= H(1 - r/2L) \text{ for } r <= 2L \\
&= 0 \text{ for } r > 2L \text{ where } r^2 = x^2 + y^2
\end{aligned} \tag{2}
$$

where L denotes the distance from hill top to the hill surface point at which height equals to half of the hilltop height H. The coordinate system x, y and z used in the study are the free steam, span wise and vertical directions with the origin at the centre of valley. Fig. 1 shows a sketch of the simplified valley models for this study, the largest blockage ratio caused by the valley models is only 6.2%. The blockage effect on flow measurement has not been corrected in this study.

A cobra probe was used to measure the mean wind velocity and turbulent components of the wind flow in the valley. The sampling frequency was set at 1000 Hz and the sampling time equals to 30 seconds. The gradient mean wind velocity of the reference flow was set at 8.5 m/s.

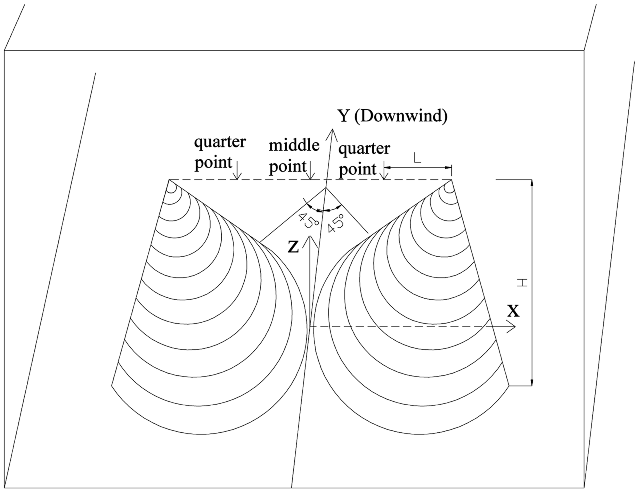


Fig. 1 Sketch of the simplified valley model

2.2. Simulated boundary layer

A neutral atmospheric boundary layer was simulated by the passive method of combination use of spires, trip board and floor roughness blocks. Six 28 cm high spires were made according to the empirical method suggested by Irwin (Irwin 1981) and a 6 cm high trip board was used to generate thick boundary layer. The spires were arranged equidistantly at the inlet of wind tunnel working section, and the trip board was connected to the spires from the bottom of wind tunnel floor. This was then followed by 10 mm cubic roughness elements covering 1.0 m long of the test section floor. The wind tunnel setup is shown in Fig. 2. The power law formulation was used to describe the simulated mean wind speed profile:

$$\frac{U}{U_r} = \left(\frac{Z}{Z_r}\right)^{\alpha} \tag{3}$$

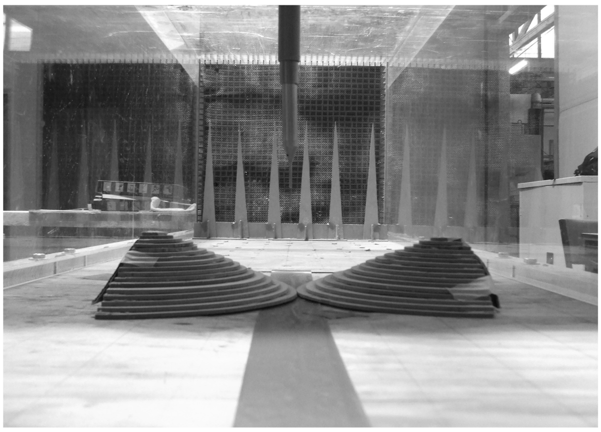


Fig. 2 Wind tunnel set up for the present study

where U is the mean velocity at a height Z; U_r is the velocity at the reference height Z_r. Fitted by the least square method, the simulated mean wind speed profile was expressed by the power law with an exponent of $\alpha = 0.2$. The simulated reference boundary layer was nearly 20 cm thick and was used for comparison with the profiles observed in the valley. Fig. 3 shows the simulated result of mean boundary layer profile at x=0, the centre position of where the valley model would be mounted, 1.5 m downstream of the inlet of work section. The lateral uniformity of the incoming flow was checked at the height of valley models in the plane of x=0 and the mean velocity variations were about 2%. Fig. 4 shows the energy spectra in the incoming flow and the fitted spectra curve according to the normally used spectrum formulation Eq. (4). According to the turbulence profile and energy spectra, the wind field scale ratio between atmosphere and wind tunnel was set at 1:2000.

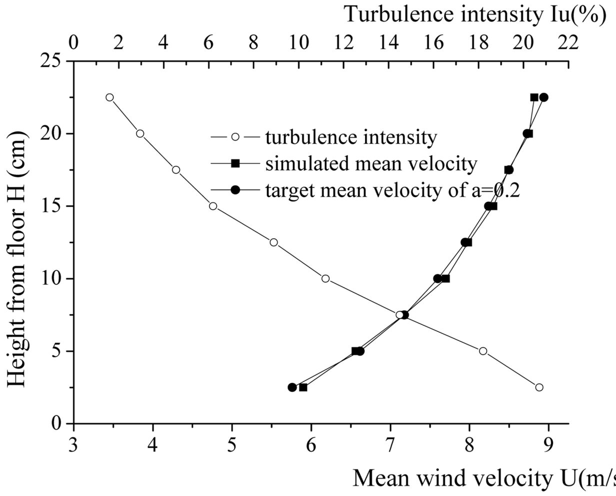


Fig. 3 Vertical distributions of mean wind velocity and longitudinal turbulence intensity of the reference flow

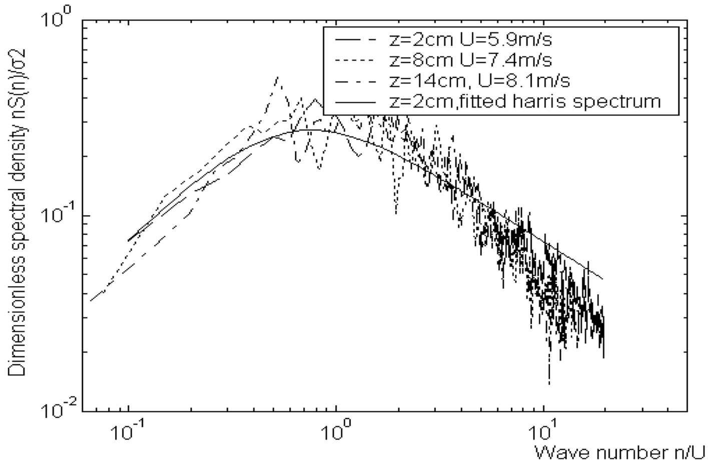


Fig. 4 Energy spectra for the longitudinal velocity component of the reference incoming flow

$$\frac{nS(n)}{\sigma^2} = \frac{0.6\left(\frac{nl_z}{U}\right)}{\left[2+\left(\frac{nl_z}{U}\right)^2\right]^{5/6}} \tag{4}$$

where $S(n)$, σ^2, U denote the power spectral density, the variance and the mean wind velocity of the turbulent flow respectively. n and l_z represent the fluctuating frequency and turbulence scale.

2.3. Influence of surface roughness on flow structure

Some researchers have emphasized on the need of consideration of the surface roughness effect on the flow over hills. Neff and Meroney (1998) examined the influence of vegetation on the wind speed-up effect on the crest. Their results showed that the hill surface covered by vegetation had lower speed-up effect as compared with the situation of smooth surface. Miller and Davenport (1998) also compared the two surface situations which referred to smooth and rough. They got similar results that the smooth surface lead to larger magnitude of the speed-up effect. The rough surface led to over 30% less speed-up effect than that for the smooth surface. Derickson and Peterka (2004) also found a faster wind flow at all levels over a smoothed terrain model as compared to a terraced terrain model, particularly in the lee regions where were mostly affected by flow separation characteristics. Cao and Tamura (2006) investigated both the hill surface and the upstream surface condition effect on the turbulent flow over hills. They modeled the rough hill surface by arranging small cubic blocks on the surface. Their results showed that under the same upstream surface condition, the rough hill surface generated lower speed-up effect. However, under the same hill surface condition, the rough upstream surface led to higher speed-up effect.

At the first stage of the present study, in order to investigate the influence of hill side surface roughness on the wind field characteristics in the valley, one of the valley models with slope 0.615 was selected for test. Two different hill surface roughness situations were studied. The original contour line hill surface was referred to "rough" and the "smooth" surface was obtained by covering the hill surface with smooth thin card board. The roughness length Z_0 were fitted to be 0.022 mm and 0.0043 mm for the respective surfaces. Fig. 5 shows comparison of the measured vertical distribution of the longitudinal velocity and turbulence intensity for the rough and the smooth hill surfaces at the middle and the quarter measuring point along the valley span wise direction.

When compared to the reference incoming flow, it is clear that at the two quarter measuring points, the magnitude of speed-up effect for the smooth surface is larger than that Δs for the rough one. Expressed in terms of the fractional speed-up ratio Δs, it has shown that for the rough hill surface is about 35% less than that for the smooth one and the fractional speed-up ratios decrease with the increase of height. At the middle measuring point, the magnitude difference of fractional speed-up ratios between the smooth and the rough situation is evident only at the low height region near the hill surface. As the height exceeds approximately 0.8H from the surface, the difference become quite small. Also, as can be seen from Fig. 5(b), the longitudinal turbulence intensity at the quarter point is relatively smaller than the corresponding value of the reference flow at the same height. In contrast to the tendency of velocity variation, the turbulence intensity value for the smooth hill surface is seen to be nearly 25% lower than that for the rough surface. Another interesting phenomenon is that the longitudinal turbulence intensity profile measured at the middle point is lower than that of the reference incoming flow for the two types of surface conditions in

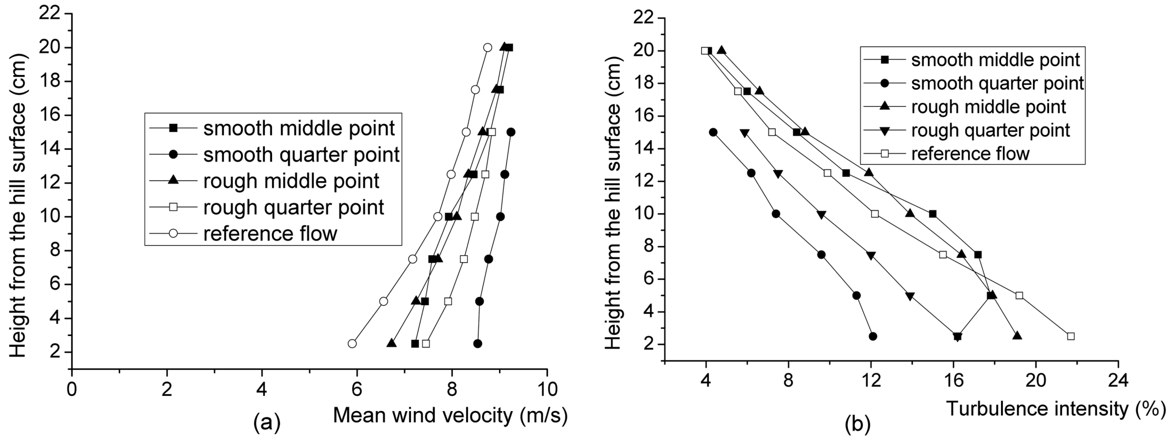


Fig. 5 Comparison of turbulent boundary layer profile in valley between the smooth and the rough hillside surface: (a) longitudinal mean velocity profile and (b) longitudinal turbulence intensity

the near surface region, approximately under 5 cm from hillside surface in the model. The smooth surface condition is seen to cause smaller turbulence intensity value than the rough surface. With the increase in height, turbulence intensity of both the smooth and the rough surface situations collapses to the reference flow value. Thus at higher height above the surface, the difference in turbulence intensity between the two surface conditions is shown to become relatively small. This result shows that surface roughness conditions have significant effect on flow structure near the surface. However, the influence becomes relative small with the increase in height especially in the middle of valley. It is interesting that the changing tendencies of turbulent flow in the middle of valley have similar characteristics with the flow over hill crests which have been extensively investigated.

2.4. Mean flow characteristics

The four generic valley models with different hillside slopes were tested to investigate the wind flow characteristics in the valley as well as the relationship between the speed-up effect and hillside slopes. All the four models have rough surfaces made by plywood according to 3 mm contour line steps in order to simulate the roughness of real hill surface. Fig. 6 presents the test results of the mean velocity profile of the four valley models. The observed change of mean velocity profiles in the valley, when compared to the reference profile, is the decrease of the exponent of power law distribution as expected due to speed-up effect. At the middle measuring point, mean velocity profiles decreased gradually with the increase of hillside slopes. If the least square method was utilized to fit the curves, the power law exponents were 0.14, 0.132, 0.115 and 0.102 respectively for the four models. Although the exponent at quarter measuring point position was also reduced, it seems that the hillside slope had little effect on it. The exponent of mean velocity profile had nearly the same value of 0.109 for all models tested except for the minimum slope case which has got a slightly larger value. It is clear that the mean velocity profiles in the valley vary along the span wise direction. Therefore, the span-wise correlation effect should be considered when determining the wind load on structure, especially for the case of a long-span bridge across the valley.

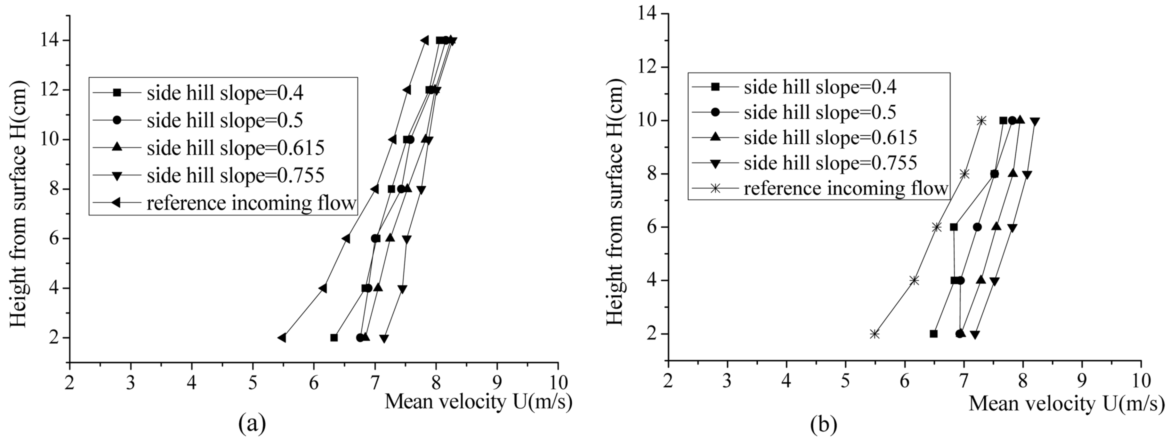


Fig. 6 Mean velocity profile inside the valley at (a) middle point position and (b) quarter point position

As the mean velocity plays a crucial role in practical wind engineering applications, perhaps one of the most important questions about mean velocity in complex terrain is to assess the speed-up effect due to the local topography. From the vertical distribution of the mean velocity at the position of the middle and the quarter measuring points, the values of fractional speed-up ratios were calculated. Fig. 7 presents the profiles of the fractional speed-up ratios at the middle and the quarter measuring points under different hillside slope situations. The fractional speed-up ratios decreased exponentially with the increase in height, and at middle measuring position, the decrease tendency was more rapid than that at the quarter measuring position. Meanwhile, at the same height from the surface, the speeds-up effect at the quarter point was slightly larger than that at the middle point under the same hillside slope. The larger hillside slope induced more evident speed-up effect. For the profiles of speed-up ratios, as was pointed out by Cao and Tamura (2006), there should be a

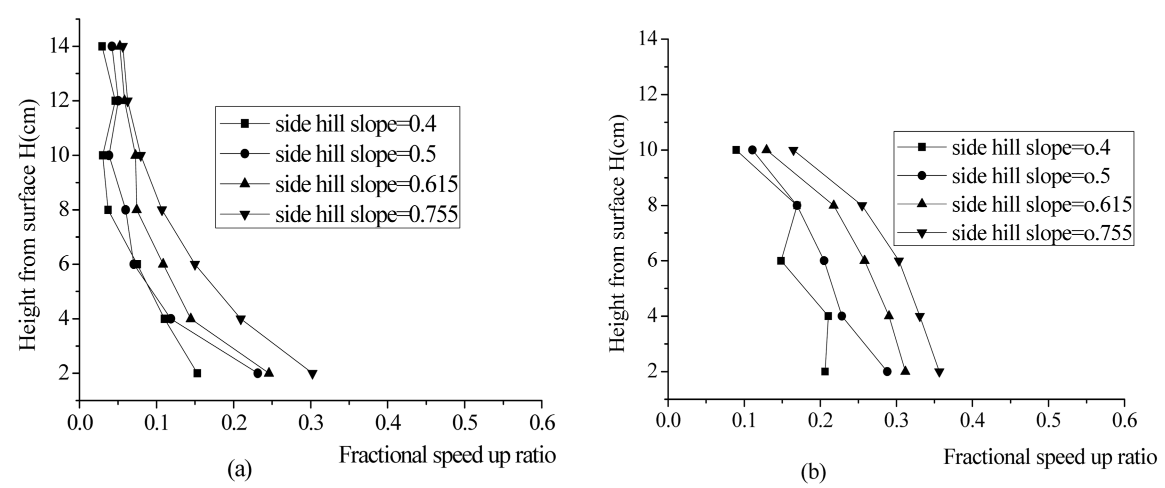


Fig. 7 Profile of fractional speed-up ratios of mean velocity at (a) the middle point position and (b) the quarter point position

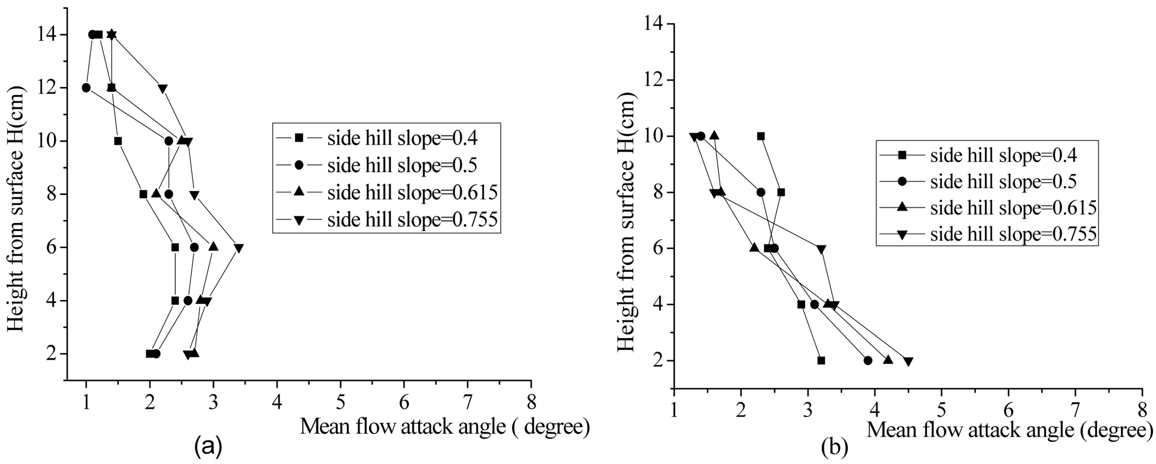


Fig. 8 Vertical profile of mean flow attack angle under situations of different hillside slopes at (a) middle point position and (b) quarter point position

height Z_{max} where Δs reaches maximum in the profile because of the demand of no-slip condition on the hill surface. Unfortunately, we could not detect them because the measurements did not reach close enough to the surface. The fractional speed-up ratios at the height of the hilltop which are important for determining the design wind speed for the long-span bridge across the valley were around 0.1 at the middle measuring point position and larger than 0.2 at the quarter measuring point position. It again indicated the three dimensional characteristics of wind field in the valley.

For the determination of the design wind speed for structures, beside the mean velocity, another important factor related to mean flow should be the attack angle of the mean flow. This is especially important for structures like long-span bridges. So in our study, the variation of mean flow attack angles was also studied. Fig. 8 shows the mean flow attack angles varied with the height in the valley. Due to the error and uncertain factors in the test, the observed values were relatively scattered, but some tendency still can be derived. At the centre of the valley, the mean flow angle increased with the height and then decreased when reached certain height. At the height of the hilltop where normally will be the bridge deck elevation, the mean flow angle fall into the section of 2 to 3 degree. At the quarter point position, the mean flow angles decreased with the increase of height. At the height of the hilltop, the values of mean flow angles were generally larger than 3 degree. So when determining the design wind speed for structure located at valley terrain, the wind attack angle should be considered carefully.

2.5. Turbulent flow characteristics

Turbulence characteristics also play important roles in the field of wind induced vibration and structure's safety. It is of interest to know turbulence characteristics of the wind field in the valley. Fig. 9 shows the longitudinal turbulence intensity in the valley models under situations of different hillside slopes. As can be seen, at the middle measuring point the turbulence intensity is reduced due to the speed-up effect near the hill surface as compared with the reference incoming turbulent flow. Also the larger the hillside slopes, the larger decrease in turbulence intensity it becomes. With the increase in height, the turbulence intensity becomes nearly unchanged. There is little modification

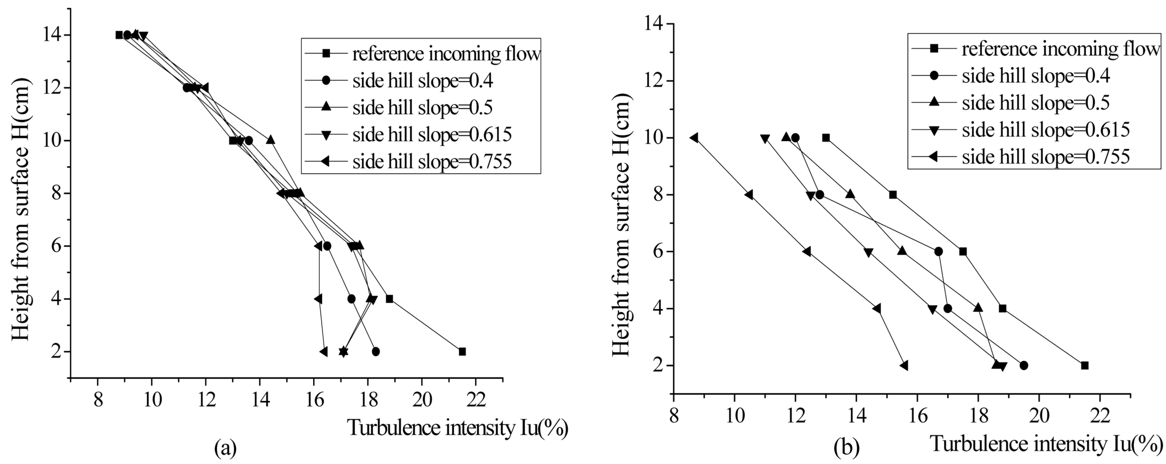


Fig. 9 Vertical profile of longitudinal turbulence intensity under situations of different hillside slopes at (a) middle point position and (b) quarter point position

to the turbulence in the flow above the height of the hilltop. While at the quarter point position, in contrast to the situation of the middle measuring point, the turbulence intensity decreased monotonically with the increase of height. The larger hillside slope would induce smaller turbulence intensity. The largest change in the local turbulence intensity therefore occurs for the steepest hill. At the height of the hilltop, the turbulence intensity at the quarter measuring point was generally larger than that at the middle measuring point. This phenomenon indicated the effect of the hillside surface roughness.

The normalized spectra of longitudinal component of the measured turbulent flow in the valley and the reference incoming flow are also analyzed. The valley model with hillside slope of 0.615 was used here as an example. Fig. 10 presents wind spectra measured at different heights at the middle point in the valley and that of the reference flow. There is little modification in the shape of

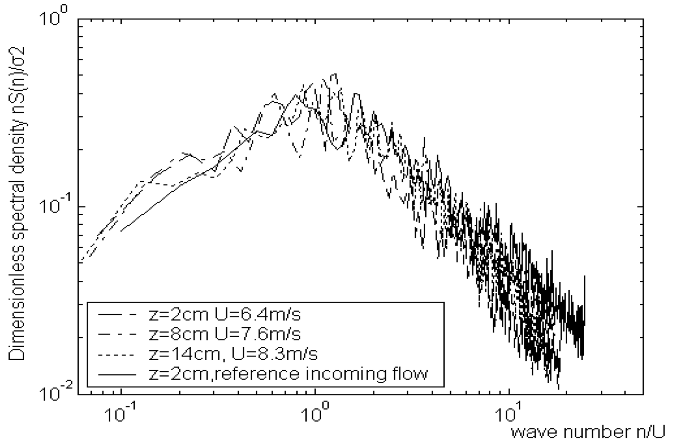


Fig. 10 Normalized spectra of longitudinal turbulent flow at the centre of the valley model with hillside slope 0.615

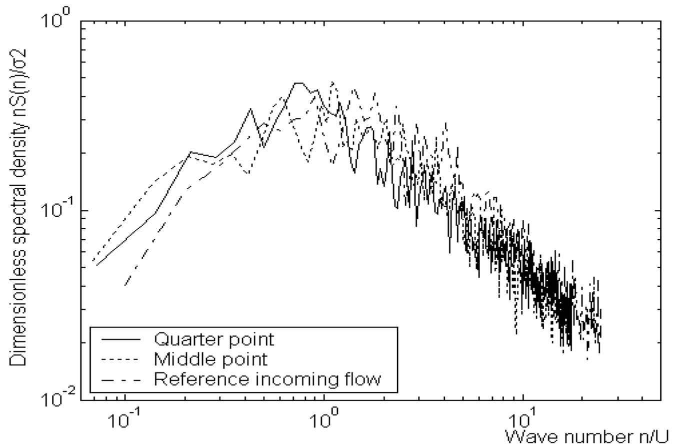


Fig. 11 Normalized spectra of longitudinal turbulent flow at the height of hilltop of valley with hillside slope 0.615

spectrum curves, but there is a slightly decrease in the spectral peak wave number in the centre of valley as compared to the reference incoming flow. This decrease is larger when the measuring position is closer to the hill surface, but the spectral peaks collapse to the value for the reference incoming flow as the height above the hill surface increases. These results are similar to those measured by Pearse at the crest of a 3D conical hill model (Pearse 1982). Fig. 11 presents the normalized wind spectra at the height of the hilltop measured at the middle point and the quarter point. Similar results were observed, as compared with the reference incoming flow. The peak wave number of the flow in the valley from the middle measuring point is seen to have a slightly smaller value than that from the quarter measuring point.

In spite of the simplicity of the models, the observed results indicate that the following conclusions can be made for the case of the real terrain:

(1) Due to the speed-up effect, it is not suitable to describe the mean wind speed profile by the power law using the same roughness exponent along the span-wise direction in the valley terrain. Significant changes of the mean flow attack angles are observed in the valley.

(2) The fractional speed-up ratios in the middle of valley decrease faster with the increase of height than that at the position near the hillside. Also at the height of the hilltop level, the speed-up effect is more evident at the position nearer to the hillside.

(3) The longitudinal turbulence intensity near the ground level in the valley is reduced due to the speed-up effect. Also there is little change in the structure of the wind velocity fluctuation as flow moves through the generic valley models.

3. Real terrain model tests

3.1. Facility and real valley terrain models

In order to verify the results obtained from the simplified models, wind tunnel tests of a real valley terrain were also conducted in a closed-circuit wind tunnel in the Wind Engineering Research

Centre, Hunan University of China, which has a working section of 5.5 m wide, 4.4 m high and 15 m long, equipped with a 4m diameter turntable, and the wind speed ranging from 0 to 16 m/s. The selected real valley terrain is located at the mountainous area in the western part of Hunan Province, China, where a super long-span suspension bridge, the Aizhai Bridge, is designed across a deep valley with a main span of 1176 m. The perspective of the real valley is shown in Fig. 12. The axes of the valley extend along the NE direction, which is perpendicular to the span of the bridge. According to the experimental objectives and the facility conditions, the real terrain model was made in a relatively large scale of 1:500 with a diameter of 4 m, which takes the middle point of the proposed bridge span as the centre of the model. This real terrain model causes about 6.6% blockage ratio of the wind tunnel working section. Fig. 13 shows the real terrain model installed on the turntable 12 m downstream of the inlet of working section. The model was made from thick composite foam with 5 mm step according to the mapped contour lines in order to simulate surface roughness appropriately. Continual transitions were also provided from the approach terrain to the major topographical features, in particular, for wind directions where the real terrain model was too

Fig. 12 Perspective of the selected real valley terrain

Fig. 13 1/500 scale model installed in the wind tunnel

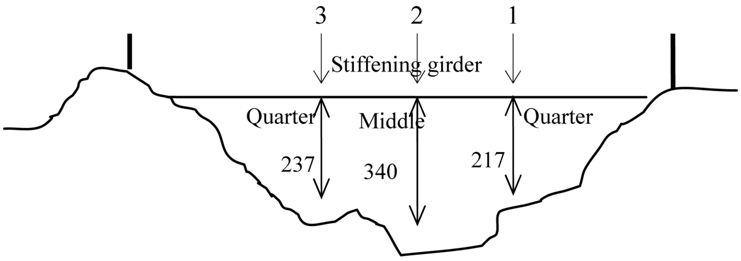


Fig. 14 Sketch showing the measuring points (unit: m)

big for the wind tunnel working section.

According to the meteorological data provided by the local weather station, the wind field at the open flat area in front of the selected valley terrain can be represented by the power law distribution with an exponent of 0.16. In order to reflect the relationship of the wind field in the valley and the representative one over the open flat area in front of the valley, the normally used passive method of the combination of spires and floor roughness arrays was used to simulate the reference wind field. A well-developed boundary layer of 0.9 m depth at a distance 10 m downwind of the spires was generated with a nominal scale of 1:500. The simulated profile of the mean wind agrees well with the target one which is represented by the power law distribution with an exponent of 0.16.

Measurements were carried out at 7 representative angles in the range of $\pm 30^{o}$ with interval of 10^{o} where the wind direction along valley axes was defined as 0^{o}. The positive direction followed the clockwise direction. A sketch showing the arrangement of measuring points of 1, 2 and 3 is illustrated in the Fig. 14, corresponding to the east quarter point, the middle point and the west quarter point of the bridge span respectively. The cross-hot wire probe was used for the measurement of the turbulent flow. However, as pointed out by Ishihara, *et al*. (1999), the accuracy of cross-hot wire probe in the wake region reduced greatly, which cannot give reasonable results due to the existence of the reverse flow. So the cross-hot wire probe was only employed at 0^{o} wind direction and a single hot wire probe was used at other wind directions.

3.2. Results of the real valley terrain models

The plots of mean velocity profile are presented in Fig. 15. Some care needs to be taken when comparing the measured mean speed results in the valley model with the reference profile. The 0 position of the vertical ordinate in Fig. 15 is set at the height of the proposed bridge deck which is at the same level as 340 m for the reference profile. If the power law formulation is adopted to describe the mean speed profile, the power law exponent can be derived by using the least square method to fit the profile curve. The fitted exponents a of mean speed profile under different test situations are shown in Table 1. Though the mean velocity profiles measured at different measuring points show quite different tendency, the qualitative similarity with the results from simplified models is still obvious when taking the local topographic features of the real valley terrain into account.

At the east quarter measuring point, the mean speed distributions under different approaching wind directions were rather scattered. When the wind came from positive directions, the mean speed profiles have nearly the same tendency of small exponents of 0.091, 0.067 and 0.059 corresponding

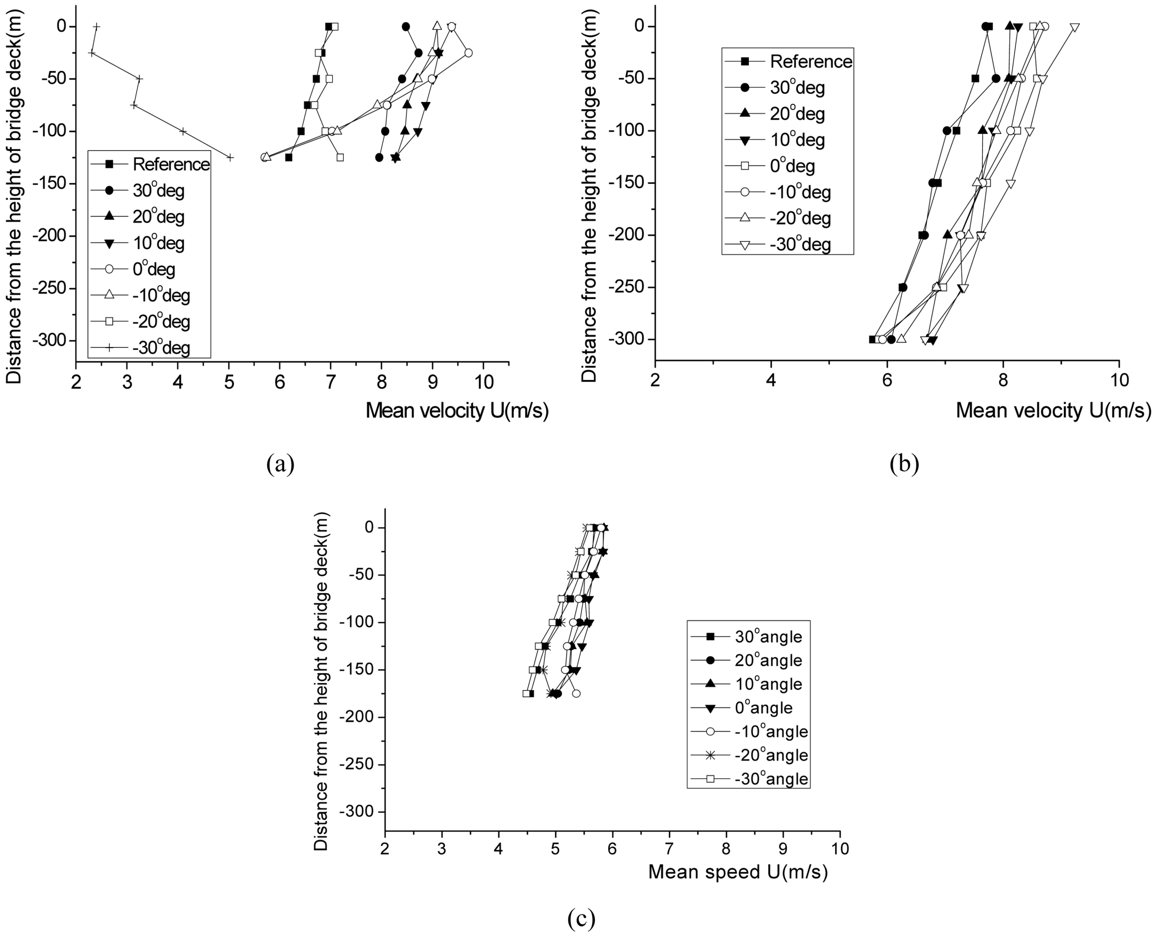


Fig. 15 Mean velocity profile at measuring points of (a) east quarter point 1 under various wind directions, (b) middle point 2 under various wind directions and (c) west quarter point 3 under various wind directions

Table 1 Fitted power law exponents for measuring points under various directions

Fitted exponents α		Wind directions						
		-30°	-20°	-10°	0°	10°	20°	30°
Measuring points	1	-0.586	-0.003	0.368	0.390	0.091	0.067	0.059
	2	0.214	0.255	0.268	0.245	0.161	0.128	0.126
	3	0.137	0.071	0.037	0.010	0.113	0.085	0.136

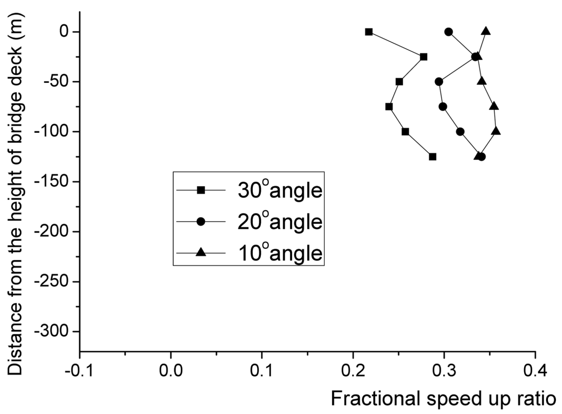
to the wind directions of 10°, 20° and 30° respectively, this change of exponents seems to be the result of the speed-up effect of the valley terrain. This tendency is similar to the results obtained from the simplified models. When the approaching wind direction turned from 0° towards the negative directions, firstly, the mean velocity became lower near the mountain surface which led to the large exponents of the mean velocity profile. Then the wind speed at high measuring positions reduced significantly, particularly for the -30° wind direction. Even negative exponent of the mean speed profile was observed, as shown in Fig. 15(a). This type of change may mainly caused by the local topographic features of the mountains near the measuring position. Under the specific wind direction situation, the local mountain blocks a great part of the approaching wind which accounts for the negative power law exponent of the mean velocity profile.

The mean velocity profiles measured at the middle point 2 in Fig. 15(b) show similar tendencies to that obtained from the simplified model tests. Under the situations of the positive approaching wind directions, the fitted exponents are generally smaller than the value of the undisturbed reference profile. However, under the situations of 0° and negative angle, the fitted exponents are slightly larger than the reference one. The small hill in front of the valley entrance may account for these different results.

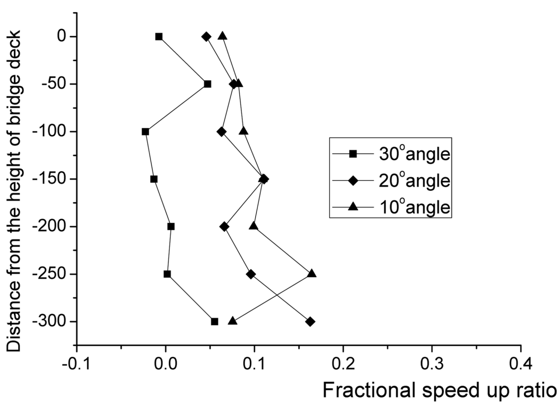
The mean velocity profiles measured at the west quarter measuring point are shown in Fig. 15(c). The main feature of the measured results is the general decrease in wind speed as compared to the reference profile under all the approaching wind directions measured. The irregular rolling mountain at the west side of the valley may account for these phenomena, and the speed-up effect induced by the valley terrain leads to the smaller values of the fitted power exponents.

As can be seen in the real valley terrain model, the mean wind speed profiles vary greatly with the measuring points and the approaching flow directions. For different wind directions, the mountains at both sides of the valley disturb and block the approaching flow to a different extent. As a result, the wind field distribution along the bridge span displays distinct characteristics of spatial diversity. So it is obvious that the mean velocity speed profiles in the valley cannot be described by the power law with the same roughness exponent. This result confirms the conclusion obtained from the simplified model tests.

The representative test results which were not markedly affected by the local topographic features of the valley were selected to calculate the fractional speed-up ratios. Fig. 16(a) shows the calculated fractional speed-up ratios at the east quarter measuring point 1 under the situations of the positive approaching wind directions. The fractional speed-up ratios at the east quarter measuring point fall into the range of 0.2 to 0.4, and it decreases slightly with the increase in height. From Fig. 16(b) it



(a)



(b)

Fig. 16 Fractional speed-up ratio versus the height of measuring point for different wind direction: (a) east quarter measuring point 1 and (b) middle measuring point 2

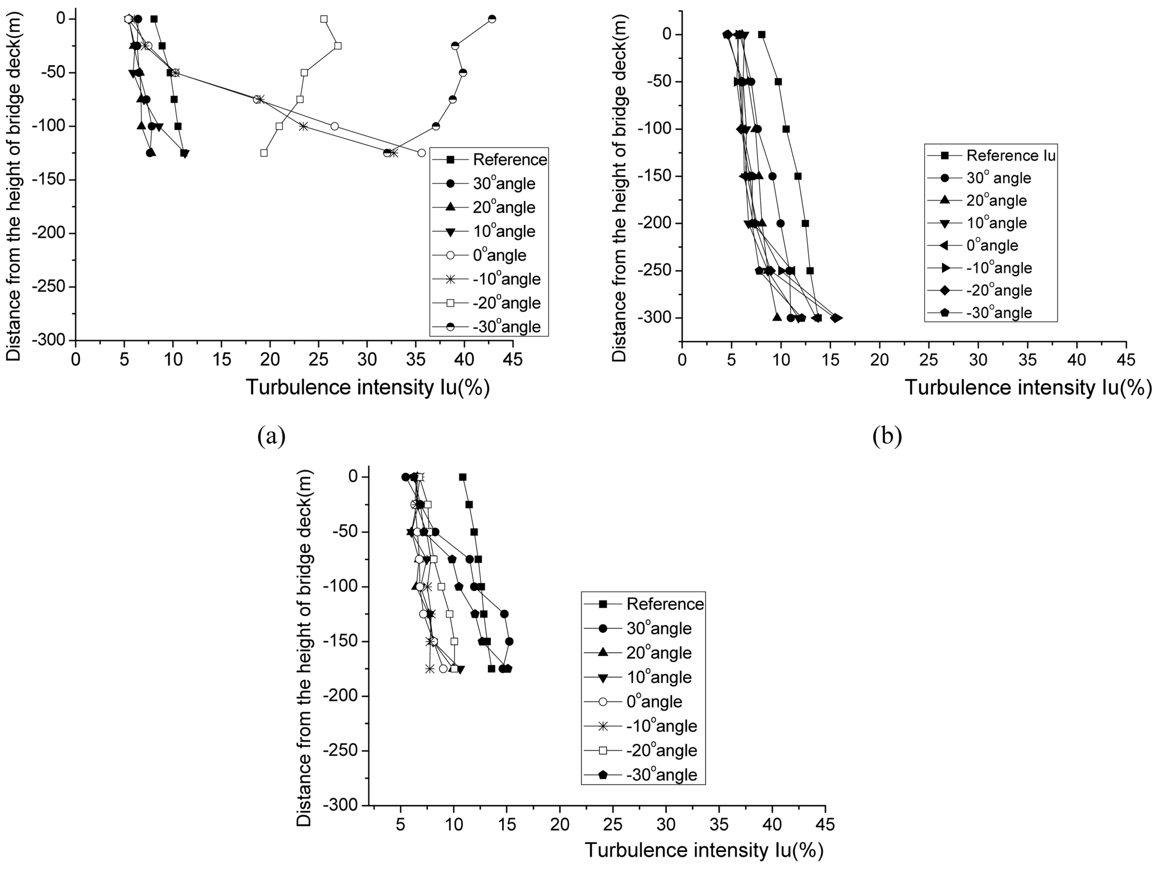
Table 2 Experimental results of attack angle at the height of typical bridge section under 0° wind direction

Measuring points	East quarter	Middle span	West quarter	Mean value
Attack angles	5.3°	4.0°	4.8°	4.7°

can be seen that the fractional speed-up ratios at the middle measuring point under the situations of the representative approaching wind directions are generally smaller than 0.2, and decrease with the increase in height. These results are seen to have similar trends as obtained from simplified model tests.

Variation of the attack angles of the mean wind was also investigated. The attack angles of the mean wind at the height of the proposed bridge deck under the situation of 0° wind direction were listed in Table 2. The mean value of the attack angle of the three deck positions is 4.7°. This value exceeds the range of +3° to -3°, which is usually required for the wind resistant design of bridges. The mean attack angle at the quarter position which is near the mountain is much higher than the required value.

The plots of the longitudinal turbulence intensity profiles are presented in Fig. 17. As can be seen, the observed longitudinal turbulence intensities are generally smaller than the corresponding value



(c)

Fig. 17 Vertical profile of longitudinal turbulence intensities under the situation of different approaching wind directions: (a) east quarter measuring point 1, (b) middle measuring point 2 and (c) west measuring point 3 of the undisturbed reference wind. These results may mainly be caused by the speed-up effect of the valley terrain, which is similar to the situation of the simplified models tests. The turbulence intensity I_u measured at the middle span measuring point 2 at the height of the proposed bridge deck exhibited a relatively steady trend tending to a value of 6% for different wind directions. However, at the measuring points of 1 and 3 near the mountains at both sides of the valley, the turbulence intensity showed large fluctuations with the change of wind directions and sometimes relatively large values were observed. This may be induced by the disturbance of the mountains located at both sides, as also found by Cheung, *et al.* (2003) the wind flow separated on the leeward side of the mountain around the two sides cause significant distortion.

4. Conclusions

The fundamental information obtained from the simplified valley models appears to be useful for understanding the wind field characteristics of a real valley terrain. Significant changes in the mean wind direction and the speed-up effect of the mean wind velocity are observed in the valley terrain. It has shown to be unsuitable to describe the mean wind velocity profiles by the power law with the same roughness exponent along the span direction in the valley terrain. The longitudinal turbulence intensity near ground level in the valley is reduced due to the speed-up effect. The investigation of the wind field characteristics in the valley terrain provides the information necessary for determining the design wind speed of structure in the valley such as the long-span bridge across the valley. However, the local topographic features of a real valley terrain may also cause flow separation and significant distortion to the wind field characteristics in the valley. The range of distortion depends heavily on the angle between the approaching wind direction and the axis of the valley terrain.

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