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Wind Tunnel Experimental Research on the Effect of Col Topography on Wind Environment

(Penyelidikan Eksperimen Terowong Angin ke atas Kesan Topografi Kol Alam Sekitar Angin)

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ABSTRACT

Investigation of meteorological disasters caused by small-scale topography shows that flashover due to wind age yaw occurred quite often where col topography existed. Considering that the distribution pattern of wind profile at different locations of a col topography is not clear, this paper, with wind tunnel tests, studied the influenced of such topographic features of a col as hill slope and valley mouth width on the wind profile at different locations. The results of wind tunnel tests indicated that over-hill wind has a stronger effect on wind velocity correction coefficient than does valley wind, that compared to flat terrain wind velocity, the maximum speed-up amplitude of wind velocity at valley throat and hill summit reach 33 and 53%, respectively, apparently higher than 10% specified in Codes, that wind velocity at valley throat increases with the increase of hill slope and decreases with the increase of valley mouth width, that wind velocity in the valley basically does not go up when the slope of one hill side is smaller than 0.1 and that wind velocity at the same non-dimensional height of a 3D hill summit increases with the increase of hill height.

Keywords: Col; wind tunnel test; wind velocity correction coefficient

ABSTRACT

Kajian bencana meteorologi yang disebabkan oleh topografi berskala kecil menunjukkan bahawa lampau kilat kerana anginan rewang berlaku agak kerap dengan kol topografi wujud. Memandangkan bahawa pola taburan profil angin di lokasi yang berbeza daripada topografi kol tidak jelas, kertas kerja ini dengan ujian terowong angin, mengkaji pengaruh ciri-ciri seperti topografi kol sebagai cerun bukit dan lembah lebar mulut ke atas profil angin di lokasi yang berbeza. Keputusan ujian terowong angin menunjukkan bahawa angin lepas bukit mempunyai kesan yang kuat pada pekali pembetulan halaju angin daripada angin lembah atas dengan halaju angin rupa bumi rata, amplitud kelajuan sehingga maksimum halaju angin di lembah tekak dan puncak bukit masing-masing pada 33 dan 53%, nampaknya 10% lebih tinggi daripada yang dinyatakan dalam Kod, bahawa halaju angin di lembah tekak bertambah dengan peningkatan cerun bukit dan berkurang dengan peningkatan lebar mulut lembah, bahawa halaju angin di lembah itu pada dasarnya tidak naik apabila lereng bukit satu bahagian lebih kecil daripada 0.1 dan bahawa halaju angin pada ketinggian tanpa dimensi yang sama sidang kemuncak bukit 3D meningkat dengan peningkatan ketinggian bukit.

Kata kunci: Angin pekali pembetulan halaju; kol; ujian terowong angin

INTRODUCTION

When air flow enters a col valley, it flows from an open area into a narrow area, in which case the flow area will be compressed, the air flow will converge toward the valley center and a funneling effect will be generated, resulting in significant increase of wind velocity. A large number of researches have been conducted on hilly terrain wind filed by scholars abroad and at home. Jackson and Hunt (1975) first put forward an analytical algorithm for two-dimensional hill speed-up effect not considering flow separation in 1970s and following this, Kaimal and Finnigan (1994) further considered the influence of flow separation. Miller and Davenport (1998) studied the characteristics of hilly terrain wind filed with 12 continuous two-dimensional hills with wind tunnel tests. Taking advantage of development in fluid simulation and computer hardwares, Taylor and Lee (1984) proposed an algorithm for wind velocity speed-up effect based on boundary layer numerical simulation, which could take the influence of hill roughness into account (Ashraf et al. 2014, 2013). By numerical simulation, Li et al. (2010) proposed a correction algorithm to calculate the mean wind velocity speed-up ratio in hilly terrain. Through wind tunnel tests, Sun et al. (2011) carried out further studies on the characteristics of fluctuating wind in hilly terrain wind field and came up with a new distribution model for fluctuating and mean wind velocity. Focusing on the wind velocity speed-up effect of hilly terrain with steep slope, Wei et al. (2010) proposed a logarithmic-law calculation model for wind velocity in hilly terrain and pointed out that it was more accurate than the exponential-law one in terms of the description of speed-up effect of near-surface wind velocity in hilly terrain (Ashraf et al. 2012a, 2012b, 2012c).

Most of the studies on the characteristics of hilly terrain wind filed were carried out with a single two-dimensional or three-dimensional hill while less attention was paid to col topography made up of two three-dimensional hills. Chen et al. (2008) tested the wind field characteristics of mountainous valley in wind tunnel, whose results showed that the distribution of mean wind profile at different locations of the valley had obvious disuniformity and could not be simulated as a uniform wind profile, suggesting that the height of measuring points and the shape of mountains on both sides should be taken into account (Ashraf et al. 2011). Pang et al. (2008) explained that wind velocity in mountainous valley was mainly affected by valley wind, over-hill wind and shielding effect. Wang et al. (2008) discussed how the wind velocity correction coefficient at hill top in col topography change with the distance between hills and the hill slope using CFD software.

In this paper, wind profiles at different locations of a three-dimensional col model in several different working conditions were measured in wind tunnel tests. Based on the obtained experimental data, the effect of four topographic features, namely hill slope, valley mouth width, symmetry of hills and hill height, on the wind profile at different locations of col topography were discussed.

Definition of Wind Velocity Correction Coefficient in This Paper

In order to take the effect of topographical features on wind velocity into account, relevant design codes adopt correction coefficient, which allows the design wind velocity in complex terrain to be obtained on the basis of flat terrain wind velocity. It is specified in Load code for the design of building structures (GB50009 2006) that for valley mouth or mountain pass facing the same direction as wind blows, the value of wind pressure correction coefficient is between 1.2 and 1.5 which is 1.095~1.225 if converted to wind velocity correction coefficient. Code for Design of 110 kV~750 kV Overhead Transmission Line (GB50545 2010) prescribes that the number should be 10% larger than that for flat terrain wind velocity if no reliable data are available.

This paper also adopt wind velocity correction coefficient to take the effect of pass topography on wind velocity into account and it is defined as the ratio of measured wind velocity to incoming flow reference wind velocity, i.e.:

$$\eta_{Vz} = \frac{V_{Tz}}{V_{Cz}}, \tag{1}$$

where η_{Vz} is wind velocity correction coefficient; V_{Tz} is the measured wind velocity at the height z from hill surface; and V_{Cz} is the incoming flow reference wind velocity at the height z from ground surface.

Meanwhile, to effectively describe the relationship between wind velocity correction coefficient and height, non-dimensional height is defined as:

$$\eta_{hz} = \frac{z}{H}, \tag{2}$$

where z is the distance of measure point from hill surface; and H is the hill height.

In order that the experimental results for each model can be compared conveniently so that the influence of col topography on wind velocity can be summarized, the following passages will mainly explore the distribution pattern of wind velocity correction coefficient along non-dimensional heights (Ashraf et al. 2012c, 2012d, 2012e).

Parameterization and Making of Pass Model

Parameterization of Col Model

In order to facilitate wind tunnel tests, the three-dimensional col model was made standardly, which was parameterized with the sine curve shown in (3) according to its slope, height and the width of valley mouth. Its cross-section is shown in Figure 1,

$$\begin{cases} \frac{z}{H}\sin^2\left(\pi x / 4L_h\right) & |x| < 4L_h \\ 0 & others \end{cases}, \tag{3}$$

where H is the hill height; and L_h is the distance from half hill height to hill peak. Hill slope $s = H/2L_h$.

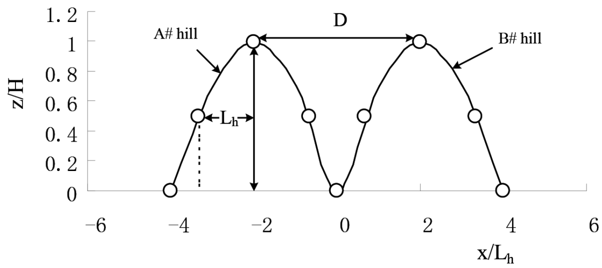


FIGURE 1. Parameter model of col

Making of Wind Tunnel Model

In this study, 6 different col topographies were selected with maximum prototype height being 100 m. In view of the actual dimension of China Aerodynamics Research and Development Centre 8 m × 6 m wind tunnel section and the demand of test accuracy, the scale for model making was decided as 1/500 to ensure that the blockage ratio of wind tunnel was around 5% or less, on which basis the specific size of each model is shown in Table 1. The relationship between the above-mentioned topographic features and distribution pattern of wind profile were studied by changing the height, slope, valley mouth width and symmetric property of the two three-dimensional hill models.

TABLE 1 . Size of wind tunnel test model

Model Number	Model height H (m)		Slope S		Diameter of model bottom $4L_h$ (m)		Width of valley D (m)
	Hill A	Hill B	Hill A	Hill B	Hill A	Hill B	
YK-1	0.1	0.1	0.1	0.1	2.0	2.0	$4L_h$=2
YK-2					2.0	2.0	$5.6L_h$=2.8
YK-3	0.1	0.1	0.3	0.3	0.667	0.667	$4L_h$=0.667
YK-4					0.667	0.667	$5.6L_h$=0.934
YK-5	0.1	0.2	0.3	0.3	0.667	1.333	$2L_{h1}+2L_{h2}$=1
YK-6	0.1	0.2	0.1	0.3	2.0	1.333	$2L_{h1}+2L_{h2}$=1.667

WIND TUNNEL TESTS

Wind tunnel tests were carried out in boundary layer wind tunnel, in which type-B flow field was simulated with 'spire + roughness element' method. TFI -cobra probe was used to test wind velocity, which can test wind velocity at different height accurately under the control of stepping motor. The probe was 155 mm long with the maximum width of probe head being 2.6 mm (Ashraf et al. 2010). The accuracy for wind velocity test was 0.2 m/s and that for yaw angle test was 1 degree. The measure range of wind velocity was 2~50 m/s.

TEST FLOW FIELD

In order to satisfy the demand of small-scale topography wind tunnel test, type-B turbulent flow field wind field was adopted. By referring to load code for the design of building structures, it can be known that wind velocity V changes with height in accordance with the equation following:

$$U = U_{10}\left(\frac{z}{10}\right)^{\alpha}, \quad (4)$$

where Z is height, U_{10} is wind velocity at 10 m height; and $\alpha = 0.16$ is the topographic index.

Passive simulation method, namely 'spire+ roughness element' method, was used to simulate corresponding wind field, in which evenly spaced spires and cuboid roughness elements were set up 6-10 m away from the model towards the upstream of incoming flow. In the test, the reference wind velocity point was set at a height of 1.0 m away from the model front to make sure that the measured velocity is the actual wind velocity of incoming flow onto the model front.

The fact that the height of all the Col models were within 0.2 m posed strict demand on the wind velocity profile of flow field near the wind tunnel bottom. As the test range was between 0~0.4 m, probes were fixed onto special traverse system which was controlled by electric motor to ascend or descend so that measuring point could be set at 0.02 m interval within the range of 0.1~0.4 m. The mean wind velocity profile curve for type B wind field simulated in wind tunnel is shown in Figure 2, which is in good agreement with the target value curve calculated with equations in Load code for the design of building structures.

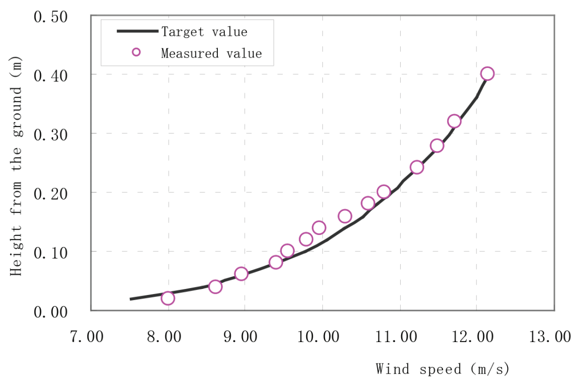


FIGURE 2. Mean wind velocity profile curve for type B wind field simulated in wind tunnel

WORKING CONDITIONS OF TESTS

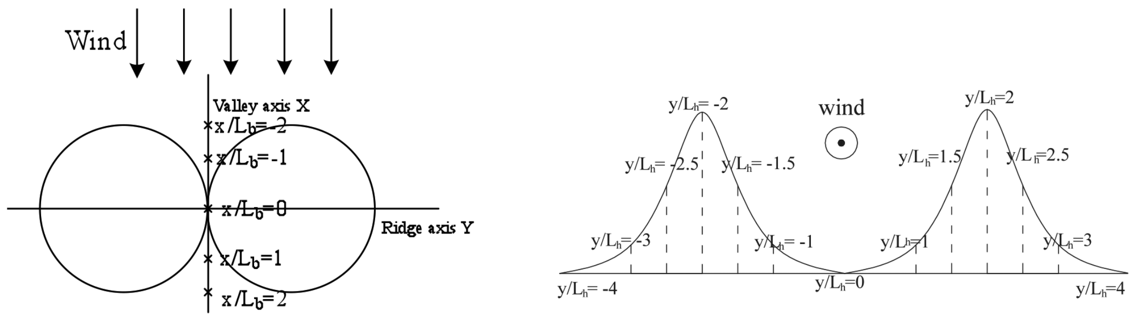
In the procedure, for 6 different three-dimensional Col mode YK-1~YK-6, the vertical wind profiles at 18 different locations (x/L_h and y/L_h) of valley central axis and ridge central axis were tested. Distribution of measuring points is shown in Figure 3. The sample photos for typical working condition in wind tunnel test are shown in Figure 4.

DISTRIBUTION PROPERTIES OF WIND PROFILE ALONG VALLEY CENTRAL AXIS

According to the results of wind tunnel test, the distribution patterns of wind profile at different locations of valley central axis for 6 Col mode were compared.

COMPARISON OF WIND PROFILE AT DIFFERENT LOCATIONS

Let's take YK-3 as an example because it has steeper slope, narrower valley mouth and more obvious change of wind velocity correction coefficient. In YK-3 working condition, the change curve of wind velocity correction coefficient η_{Vz} at five different locations along the valley center line with the variation of non-dimensional height η_{hz} is shown in Figure 5.



(a) test point distribution along the valley axis (b) test point distribution along the ridge axis

FIGURE 3. Test point distribution diagram

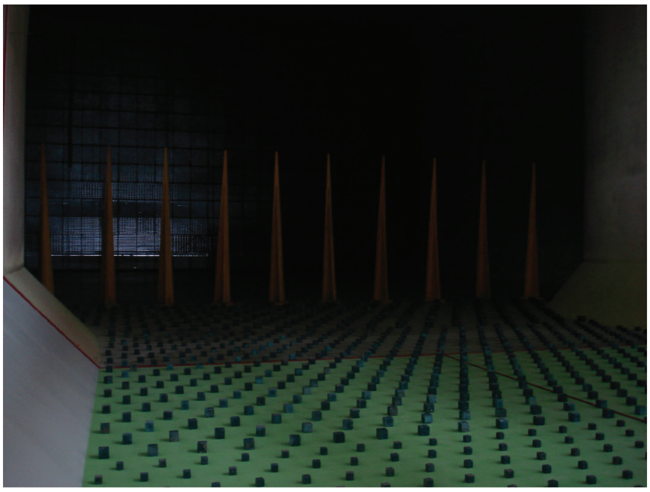


FIGURE 4. Typical working condition of wind tunnel test

The following pattern can be observed from Figure 5: The most significant speed-up effect of valley wind occurred at $y/L_h = 0$, where maximum wind velocity correction coefficient reached 1.328 and valley wind velocity increased by 33% compared to flat terrain wind velocity, much higher than the 10% increase specified in Codes for transmission line design; wind velocity correction coefficient decreased with the increase of non-dimensional height; for two points symmetric about the ridge central axis, the leeward wind velocity was higher than the windward one, indicating that streamline convergence degree at upwind and downwind side were different with the latter being higher than the former.

INFLUENCE OF HILL SLOPE

In order to discuss the influence of hill slope on the wind profile along the valley central axis, experimental results of YK-1 and YK-3 are compared in Figure 6.

The following pattern can be observed from Figure 6: At $y/L_h = 0$, the increase of slope incurs noticeable increase of wind velocity correction coefficient; at other locations, wind velocity correction coefficient is less affected by slope and the change curves of wind velocity correction coefficient at the same location of different slopes along non-dimensional height basically overlap with each other.

EFFECT OF VALLEY WIDTH

In order to discuss the effect of valley width on the wind profile along valley central axis, the experimental results of YK-3 and YK-4 are compared in Figure 7.

When valley width increased from $4L_h$ to $5.6L_h$, the following pattern of wind profile curve can be observed: With the increase of valley mouth width, valley wind speed-up effect at $x/L_h = 0$ has an obvious tendency to decrease; on the other hand, with the increase of valley mouth width, wind velocity at $x/L_h = 2$ go up slightly. The speculated reason is that the near-surface wind velocity at leeward of valley is subjected not only to valley wind effect but also to shielding effect. The increase of valley mouth width reduced the speed-up effect of valley wind (Ashraf et al. 2010), but shielding effect had an even greater effect in this respect, which explains why the near-surface wind velocity was slightly higher than that in the case of narrower valley mouth and became the same at higher locations (Bakar et al. 2014; Gharibreza et al. 2013).

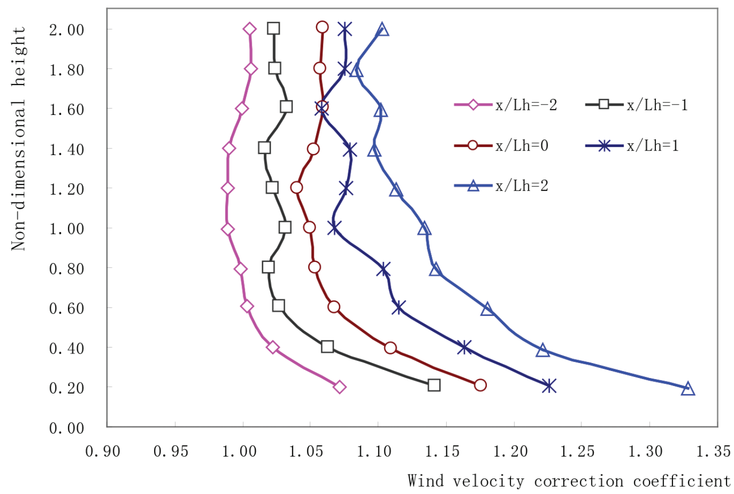


FIGURE 5. $\eta_{Vz} - \eta_{hz}$ curves of different location at the mountain valley axis

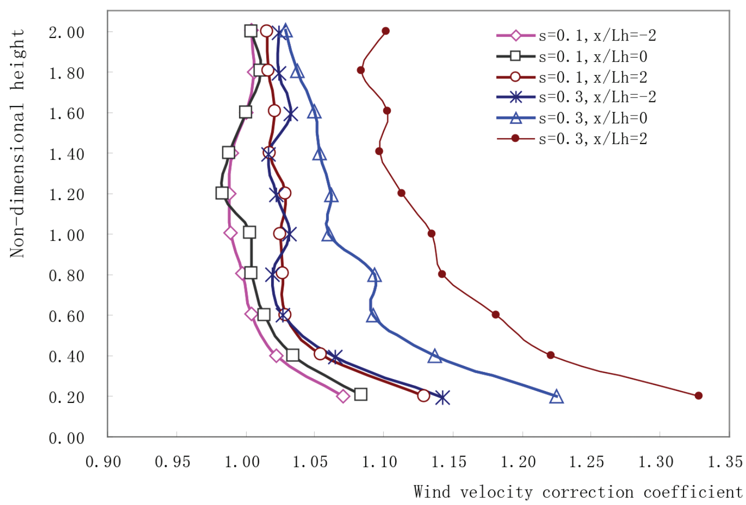


FIGURE 6. Effect of slope on $\eta_{Vz} - \eta_{hz}$ curves of mountain valley axis

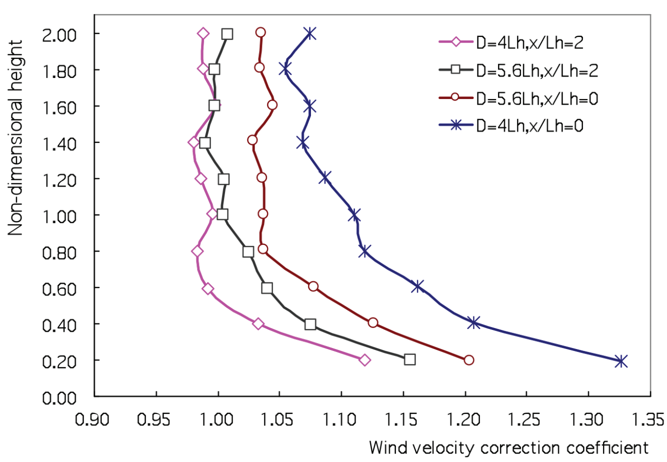


FIGURE 7. Effect of valley width on $\eta_{Vz} - \eta_{hz}$ curves of mountain valley axis

Effect of Asymmetric Hills

As shown in Table 1, the test objects under YK-5 working condition were two Col models with the same slope but different base radius and test objects under YK-6 working condition were two Col models with different slopes. In order to discuss the distribution pattern of wind profile along the valley axis when Hills A and B were not symmetric about valley axis, the experimental results of the above-mentioned two working conditions and that of YK-3 working condition were compared in Figure 8.

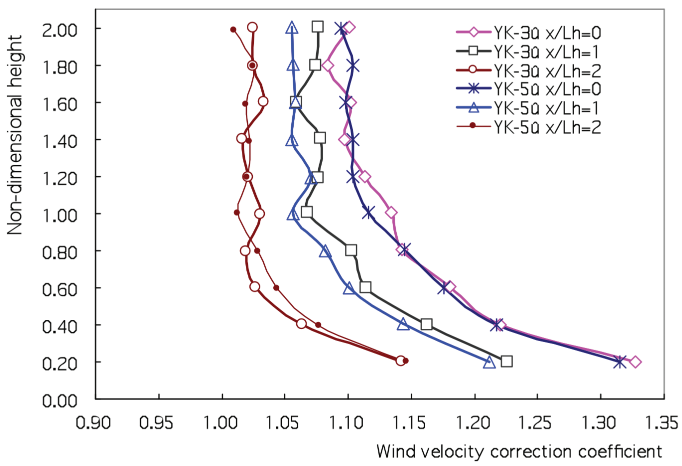
It can be seen from Figure 8 that compared to symmetric hills, the effect of asymmetric hills on the wind profile along the valley axis shows the following patterns: When the two hills forming the Col have the same slope, though their width and height are different, the speed-up effect of valley wind is consistent with that for symmetric hills (wind profile curves at different locations overlap with each other in Figure 8(a)); when the hills forming the Col have different slopes and the slope of one side is smaller than 0.1, speed-up effect of valley wind decreases noticeably because no strong streamline convergence can be generated (Ashraf et al. 2011). Compared to flat terrain wind velocity, only near-surface wind velocity increased by 12%, close to the 10% increase specified in Code for Design of Transmission line 9 (Bakar et al. 2013).

Distribution Properties of Wind Profile Along Ridge Central Axis

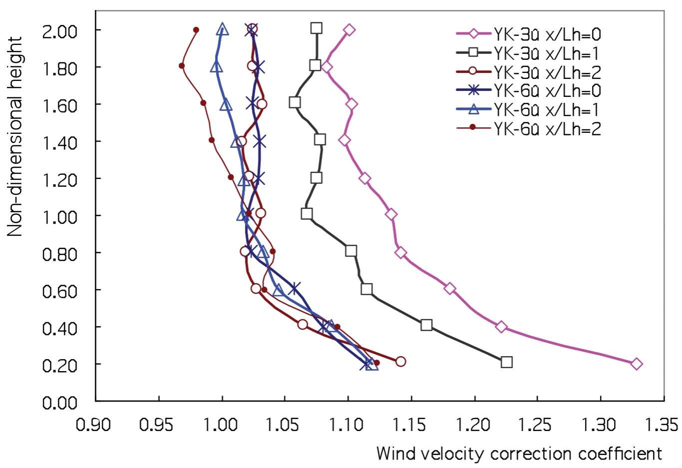
According to the results of wind tunnel test, the distribution patterns of wind profile at different location of ridge central axis for 6 Col mode were compared.

Comparison of Wind Profile at Different Locations

In YK-3 working condition, the change curve of wind velocity correction coefficient η_{Vz} at five different locations along the ridge center line with the variation of non-dimensional height η_{hz} is shown in Figure 9.



(a) Comparison of YK-3 and YK-5



(b) Comparison of YK-3 and YK-6

FIGURE 8. Effect of asymmetry hill on $\eta_{Vz} - \eta_{hz}$ curves of mountain valley axis

The following pattern can be observed from Figure 9: The maximum wind velocity correction coefficient occurred at hill peak where $y/L_h = \pm 2$, reaching 1.535 and over-hill wind velocity increased by 53% at $y/L_h = 2$ compared to flat terrain wind velocity, much higher than the 10% increase specified in Codes for transmission line design; at $y/L_h = 0$, the near-surface wind velocity correction coefficient is smaller than that at $y/L_h = \pm 2$, indicating that the effect of valley wind on the wind velocity correction coefficient is smaller than the over-hill wind effect (Yusoff et al. 2013).

Effect of Hill Height

In order to discuss the effect of hill height on the wind profile along ridge axis, the experimental results of Hills A and B, which have the same slope but different heights, in YK-5 working condition were compared in Figure 10.

The following pattern can be observed from Figure 10: Compared to the wind velocity correction coefficient at hill foot where $y/L_h = \pm 4$, that at the hill peak where $y/L_h = \pm 2$ shows significant increase and the wind velocity correction coefficient corresponding to non-dimensional height increases noticeably with the increase of the height of three-dimensional hill (Zulkifley et al. 2014).

Conclusion

In this paper, the experimental research was carried out on 6 three-dimensional Col models with different Col topographic features with wind tunnel tests. By comparison and analysis of experimental results for different model, the distribution patterns of wind velocity correction coefficient along the non-dimensional height at key points of valley axis and ridge axis were obtained, from which the following effect pattern of Col topography on wind profile were summarized:

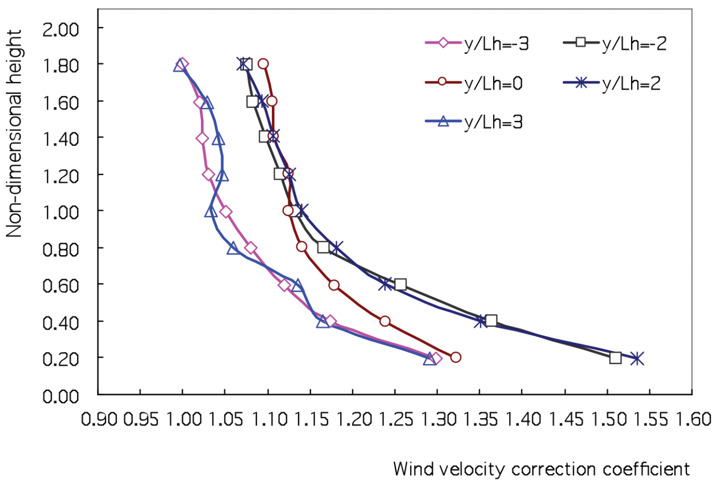


FIGURE 9. $\eta_{Vz} - \eta_{hz}$ curves of different location at the mountain ridge axis

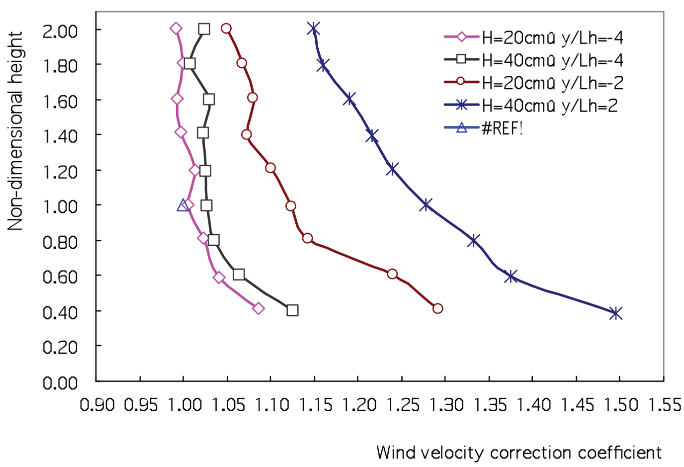


FIGURE 10. Effect of hill height on $\eta_{Vz} - \eta_{hz}$ curves of mountain ridge axis

The maximum wind velocity at valley throat was 33% higher than the flat terrain wind velocity and the maximum wind velocity at hill peak is 53% higher than the flat terrain wind velocity. Compared to the valley wind effect at valley throat, the over-hill wind effect at hill peak has a more significant speed-up effect. Both of the speed-ups exceed the 10% increase specified in Code for Design of Transmission line, which is the main cause of wind age yaw flashover of transmission lines and tower collapse. The streamline convergence on the leeward side is stronger than that on the windward side. The increase in hill slope only resulted in the increase of wind velocity correction coefficient at valley throat and when the slope of one side is smaller than 0.1, basically no increase of wind velocity in the valley is observed. The valley wind effect at valley throat weakens obviously with the increase of valley width but the weakening amplitude of the shielding effect on the leeward side is even larger. Finally, the increase in hill height significantly increases the wind velocity correction coefficient at the same non-dimensional height of the three-dimensional hill peak.

REFERENCES

Ashraf, M.A., Ahmad, M., Aqib, S., Balkhair, K.S. & Bakar, N.K.A. 2014. Chemical species of metallic elements in the aquatic environment of an ex-mining catchment. *Water Environment Research* 86(8): 77-728.

Ashraf, M.A., Yusoff, I., Yusof, I. & Alias, Y. 2013. Study of contaminant transport at an open tipping waste disposal site. *Environmental Science and Pollution Research* 20(7): 4689-4710.

Ashraf, M.A., Maah, M.J. & Yusoff, I. 2012a. Study of chemical forms of heavy metals collected from the sediments of tin mining catchment. *Chemical Speciation and Bioavailability* 24(3): 183-196.

Ashraf, M.A., Maah, M.J. & Yusoff, I. 2012b. Chemical speciation of heavy metals in sediments of former tin mining catchment. *Iranian Journal of Science and Technology* 36(A2): 163-180.

Ashraf, M.A., Maah, M.J. & Yusoff, I. 2012c. Morphology, geology and water quality assessment of former tin mining catchment. *The Scientific World Journal* 369206: 1-15.

Ashraf, M.A., Maah, M.J. & Yusoff, I. 2012d. Chemical speciation and potential mobility of heavy metals in soil of former tin mining catchment. *The Scientific World Journal* 125608: 1-11.

Ashraf, M.A., Maah, M.J. & Yusoff, I. 2012e. Chemical speciation of heavy metals in surface waters of former tin mining catchment. *Chemical Speciation and Bioavailability* 24(1): 1-12.

Ashraf, M.A., Maah, M.J. & Yusoff, I. 2011. Analysis of physio-chemical parameters and distribution of heavy metals in soil and water of ex-mining area of Bestari Jaya, Peninsular Malaysia. *Asian Journal of Chemistry* 23(8): 3493-3499.

Ashraf, M.A., Maah, M.J. & Yusoff, I. 2010. Water quality characterization of Varsity Lake, University of Malaya, Kuala Lumpur Malaysia. *E-Journal of Chemistry* 7(S1): S245-S254.

Bakar, A.F.A., Yusoff, I., Fatt, N.T. & Ashraf, M.A. 2014. Cumulative impacts of dissolved ionic metals on the chemical characteristics of river water affected by alkaline mine drainage from the Kuala Lipis gold mine, Pahang, Malaysia. *Chemistry and Ecology* 13(1): 22-33.

Bakar, A.F.A., Yusoff, I., Fatt, N.T., Othman, F. & Ashraf, M.A. 2013. Arsenic, zinc and aluminum removal from gold mine wastewater effluents and accumulation by submerged aquatic plants (*Cabomba piauhyensis, Egeria densa,* and *Hydrilla verticillata*). *BioMed Research International* 2013: Article ID 890803.

Chen, Z.Q., Li, G. & Zhang, Z.T. 2008. Model test study of wind field characteristics of long-span bridge site in mountainous valley terrain. *Journal of Experiments in Fluid Mechanics* 22(3): 54-59.

Gharibreza, M., Raj, J.K., Yusoff, I., Othman, Z., Zakaria, W., Tahir, W.M. & Ashraf, M.A. 2013. Historical variations of Bera Lake (Malaysia) sediments geochemistry using radioisotopes and sediment quality indices. *Journal of Radioanalytical and Nuclear Chemistry* 295(3): 1715-1730.

GB 50009. 2006. *Load Code for the Design of Building Structures*. The Ministry of Housing and Urban-rural Construction of the People's Republic of China. Beijing: China Construction Press.

GB 50545. 2010. *Code for Design of 110kV~750kV Overhead Transmission Line*. Beijing: China Planning Press.

Jackson, P.S. & Hunt, J.C.R. 1975. Turbulent wind flow over a low hill. *Quarterly Journal of the Royal Meteorological Society* 101: 929-955.

Kaimal, J. & Finnigan, J. 1994. *Atmospheric Boundary Layer Flows: Their Structure and Measurement*. Oxford: Oxford University Press.

Li, Z.L., Sun, Y., Wei, Q.K. & Chen, S. 2010. Numerical simulation of mean velocity speed-up effect in hilly terrain. *Engineering Mechanics* 27(7): 32-37.

Miller, C.A. & Davenport, A.G. 1998. Guidelines for the calculation of wind speed-ups in complex terrain. *Journal of Wind Engineering and Industrial Aerodynamics* 74-76: 189-197.

Pang, J.B., Song, J.Z. & Lin, Z.X. 2008. Determination method for wind-resistant design wind speed of mountainous-valley bridge. *China Journal of Highway and Transport* 21(5): 39-44.

Sun, Y., Li, Z.L. & Huang, H.J. 2011. Experimental research on mean and fluctuating wind velocity in hilly terrain wind field. *ACTA Aerodynamic SINICA* 29(5): 593-599.

Taylor, P.A. & Lee, R.J. 1984. Simple guidelines for estimating wind speed variations due to small scale topographic features. *Climatological Bulletin* 18(2): 3-22.

Wang, Z.Q., Chen, H.B. & Zhou, X.Y. 2008. Effects of yakou micro-relief on the wind loading formulation for transmission line design. *Journal of North China Electric Power University* 35(4): 23-26.

Wei, Q.K., Li, Z.L. & Sun, Y. 2010. Calculation model of speedup effect of wind velocity in hilly terrain. *Journal of South China University of Technology (Natural Science Edition)* 38(11): 4-58.

Yusoff, I., Alias, Y., Yusof, M. & Ashraf, M.A. 2013. Assessment of pollutants migration at Ampar Tenang landfill site, Selangor, Malaysia. *ScienceAsia* 39: 392-409.

Zulkifley, M.T.M., Ng, N.T., Abdullah, W.H., Raj, J.K., Ghani, A.A., Shuib, M.K. & Ashraf, M.A. 2014. Geochemical characteristics of a tropical lowland peat dome in the Kota Samarahan-Asajaya area, West Sarawak, Malaysia. *Environmental Earth Sciences* 73(4): 1443-1458.

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