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Wind Tunnel Investigation of Flow over Two-Dimensional Hills and Escarpments - A Review

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ABSTRACT

A comprehensive knowledge of the wind flow in hilly terrains is of great interest in many engineering applications, be it wind energy distribution for suitable site selection for wind farms, pollution dispersion, forest fire propagation or agro-meterological studies. Several researchers have shown that wind flow over a hilly terrain may be significantly different when compared with the wind flow over a flat terrain. Complex hilly terrains may alter the wind speed to a great extent. Therefore, this effect of terrain must be properly assessed by designers and planners to arrive at a proper wind flow distribution. This paper reviews the work done in this area over the past three decades. Wind flow over two-dimensional hills and two-dimensional escarpments investigated in wind tunnels by various researchers is presented in this paper.

1. INTRODUCTION

A proper understanding and knowledge of the atmospheric boundary layer modification due to sudden changes in the local topography is necessary to gauge the local wind conditions at a site in a hilly terrain (Bowen and Lindley, 1977). In order to assess how the wind speed, wind direction and its turbulence characteristics change as it flows over a hilly terrain, it is important to have a detailed and sufficient data on wind over a hilly terrain. The wind flow over a hilly terrain is a problem that needs to be addressed carefully given its important applications in various fields. Among the studies carried out in the past, most of the researchers studied the wind flow around hills and escarpments of various shapes and geometries; many of them focusing on the applications related to forest fire propagation due to winds (Ferreira et al., 1991), siting wind turbines and estimating their power generation potential (Carpenter and Locke, 1999), or estimation of atmospheric pollutant dispersion (Tsai and Shiau, 2011). A major

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application of the understanding of topographical effects is in the proper estimation of wind loads on buildings and structures which are located on exposed hill sites.

The modern approach to the study of boundary-layer flow over hills could be reasonably said to have started in 1970's with the series of theoretical papers, most prominent being that of Jackson and Hunt (1975), where they presented a detailed analytical solution for the flow over a low hill. Other fairly good numerical models for wind flow over hills included those of Deaves (1975) and Deaves (1980). Among others, Britter et al. (1981) carried out wind tunnel investigation of air flow over a two-dimensional hill and Pearse (1982) studied experimentally the wind flow over conical hills. Field studies on wind flow over hills include the work of Mason (1986) and Salmon et al. (1988). Studies carried out on escarpments include the prominent work of Bowen and Lindley (1977) where the authors carried out wind tunnel studies over various escarpment shapes. Other notable studies during late 1970's and early 1980's include the work of Jensen and Peterson (1978) and Jensen (1983). Lately, Tsai and Shiau (2011) studied experimentally the flow characteristics for wind over a two-dimensional escarpment.

The present review aims at summarizing the wind tunnel (experimental) studies that have been conducted on boundary layer flow over hills and escarpments over the past three decades and to review what we have learnt from them. Although several studies in the past, both numerical and experimental, have assessed the wind flow over hilly terrains (few of the authors carrying both the studies for a particular case), this paper deals primarily with the experimental studies carried out and focusses only on two-dimensional features (hills and escarpments).

2. EXPERIMENTAL INVESTIGATION ON HILLS

Research on neutrally stable air flow over hills in the past has broadened our understanding of the behavior of wind over hills of various shapes. They have also improved our understanding of how the roughness changes affect the wind over hills and how the turbulence structure changes over hills. Researchers have studied the flow over two-dimensional hills of different shapes, both single and multiple configurations. In this section, the wind tunnel studies carried on two-dimensional single hills and multiple hills is discussed.

Ferreira et al. (1991) carried out the wind tunnel simulation of flow around two-dimensional hills. The flow was studied for sinusoidal cross-section hills, for Reynolds numbers between 1.7×10^4 and 2.4×10^5. Pressure distribution on the surface of the models and the topological features described the flow around a single hill having four cross-sections, each cross-section being different. Two wind tunnels were used in the study; the first wind tunnel used for the flow system 1 was an open circuit, closed section one having 0.46×0.46 m^2 cross section and the working section as 2 m. A total of 25 pressure taps with 0.5 mm diameter along the centre section were fitted in each model. For the flow system 2, the second wind tunnel used (for the purpose of increasing the range of Reynolds number and the scale of the models) had the cross section of 1×4 m^2. This wind tunnel was also open circuit type but had an open section along the working section which was 6 m long. In one of the models, 45 pressure taps similar to the flow

system 1 models were fitted and in the other model 21 flush-mounted shear-stress sensors were fitted.

The experimental set-up comprised of two sets of models. In system 1, earlier referred to as flow system 1, four different models, all having the same height (H=60 mm) were used. The H/L ratio used for the four models were 0.75, 1.0, 2 and 4 (Fig. 1). Two similar models with H/L = 1 and H = 200 mm were used in system 2, earlier referred to as flow system 2.

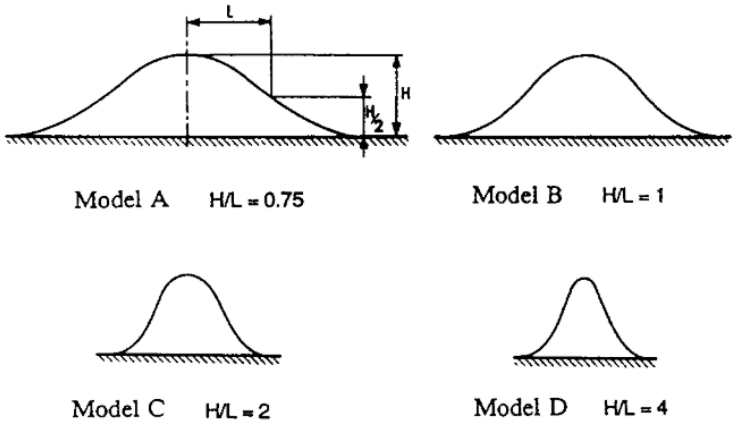


Fig. 1 Geometry of models in flow system 1 (Ferreira et al., 1991)

The flow around the four hill shapes in system 1 was analyzed by surface pressure measurements and by flow visualization. The surface pressure distribution on the hill revealed that models A and B have almost similar behaviour while models C and D show a different behaviour (Fig. 2). This was attributed to the fact that a transition in the type of flow for values of H/L in the range of 1 and 2 must have taken place. However, this fact remained unexplored by the authors. Reynolds number dependence for the flow around model B was clear when the pressure distribution was seen on the ground and on the hill for four values of Reynolds number ranging from 1.7×10^4 and 1.04×10^5. Some dependence on the properties of approaching flow (velocity-profile shape) was also observed. The shear stress distribution on model B in flow system 2 was observed to be similar to that shown by Deaves (1975) and Deaves (1980).

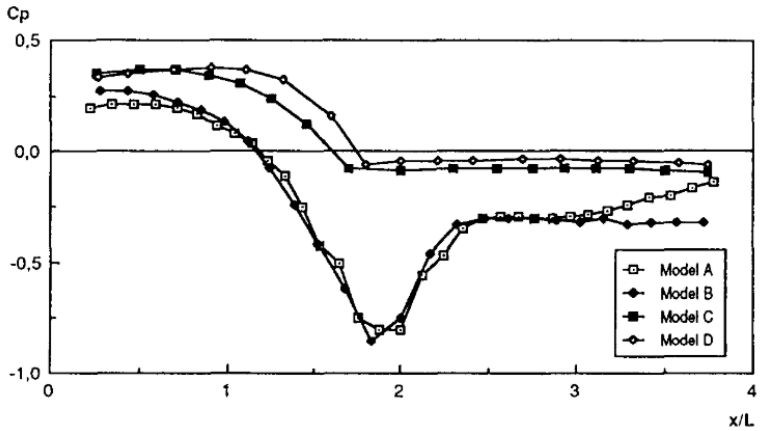


Fig. 2 Pressure distribution on the ground for each model as isolated hills (Ferreira et al., 1991)

Interaction study between two similar hills in flow system 2 for different values of distance S between the hills, where S varied between 4H and 12H, revealed that the presence of downstream hill affects the pressure distribution on both faces of the upwind hill. Pressure distribution on the downwind hill gets more affected, mainly on the upwind face. For S/H > 10, the pressure distribution was seen to be strikingly similar to the undisturbed case. Velocity profile was measured on the top of the hill for each studied case. An interesting result that came out was that for the downwind hill, there was a noticeable influence of the distance S/H on the velocity profile, the maximum velocity was nearly 70% lesser than that of the velocity on the isolated hill. This result could be of interest for installations concerning wind energy or when forecasting wind patterns from the data retrieved from sensors placed on the hill tops. Flow topology for two hills at various distances depicted that there was no stagnation or recirculating zone at the upwind hill's windward slope (Fig. 3). The bubble size grew as both the hills approached each other. Also, for the downwind hill, the size of recirculating zone tended to decrease when S decreased, until the minimum size was seen near S = 5H.

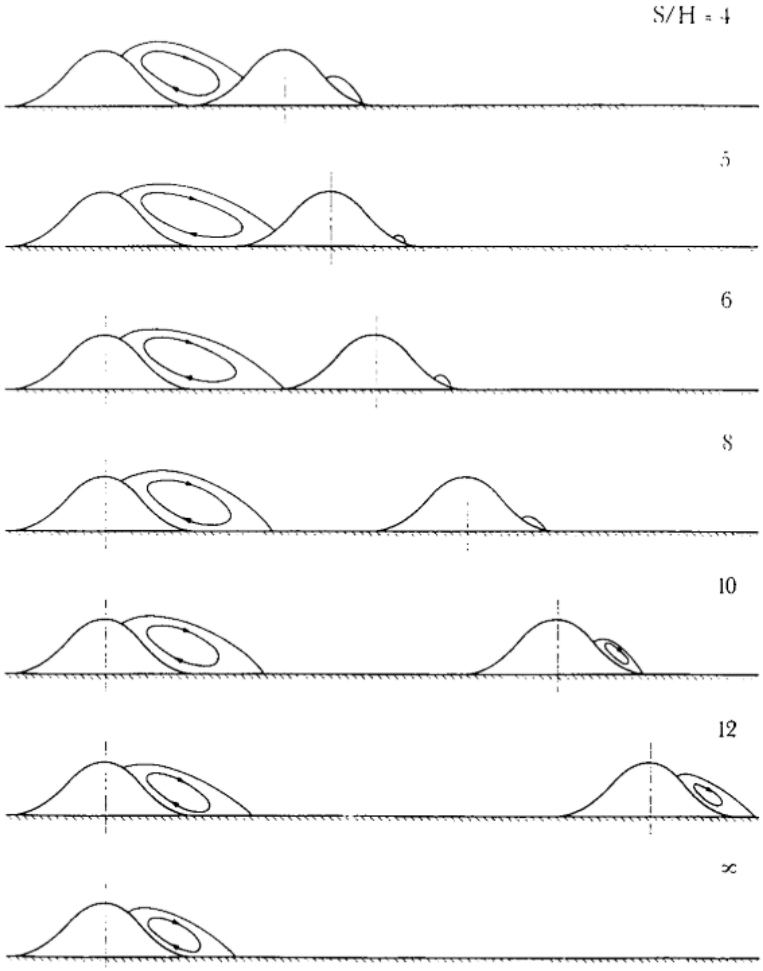


Fig. 3 Flow topology for the two hills (Ferreira et al., 1991)

Ferreira et al. (1995) carried out wind tunnel experiments of the turbulent isothermal flow around two-dimensional hills having sinusoidal cross-section, where in the authors additionally used a numerical model based on a control volume approach to calculate the flow field around the hills. Reynolds number based on the height of the hill ranged from 1.8×10^4 and 2.5×10^5. The authors studied the similar hill configuration used by Ferreira et al. (1991), only the equation used for the geometrical shapes of the hills was new. Also, two wind tunnels were used in the study for two different experiment sets similar to Ferreira et al. (1991). The only marked difference mentioned in this study with respect to the two wind tunnel set-ups was the different maximum velocity in the flow system 1 referred as S1 and the different boundary layer thickness in the flow system 2 referred as S2. Experimental results presented in the study included flow visualization, static wall pressure distribution along the hills and velocity profiles at strategic locations. For flow system 1 (S1), the size of the recirculation region was pictured by fixing wool tufts both in the surface of the models and in the bottom and lateral walls of the wind tunnel. This visualization of the flow for each hill configuration was obtained for a

Reynolds number of 8×10^4, compared with the numerically computed streamlines, and is shown in Fig. 4.

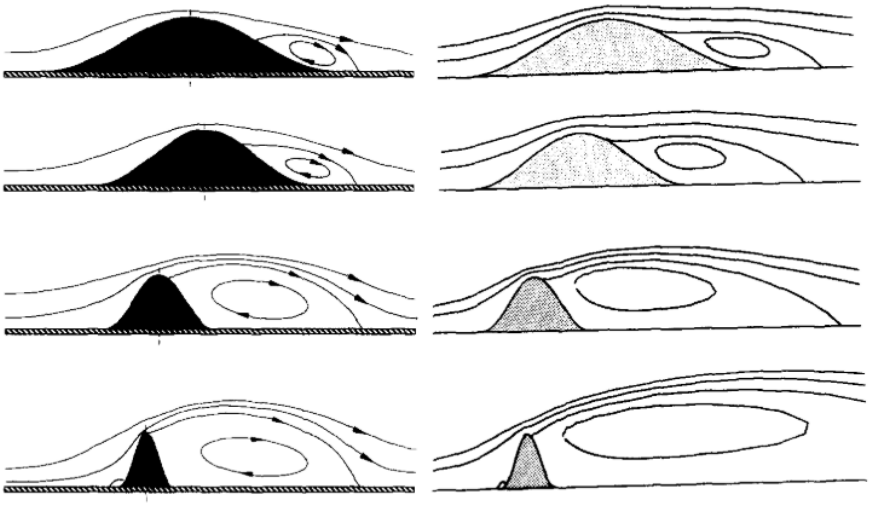


Fig. 4 Flow visualization: experimental (left) and numerical (right) results for S1 (Ferreira et al., 1995)

A strong dependency on the hill shape was observed for the size of the recirculating region, the growth of recirculation bubble being evident from second model to third model. Variation of the drag coefficient of the hill with Reynolds number depicted that the transition to a supercritical regime occurs at Reynolds number nearly equal to 9×10^4. Overall, the comparison between the numerical and experimental results agreed fairly. Both the studies, Ferreira et al. (1991) and Ferreira et al. (1995) were motivated by an application associated with forest fire propagation on hills.

Until 1997, the detailed understanding of the turbulent flow with flow separation was limited. An experimental and numerical investigation on the flow over two-dimensional hills was carried out by Kim et al. (1997) which aimed at validating the existing numerical methods and turbulence models for the prediction of different cases of wind flow over single and double hills including flow separation. Experiments were carried out for both single hills as well as continuous double hills in an open-circuit boundary-layer wind tunnel (1.2×1.2×6 m) and the results measured included mean velocity profiles, turbulence characteristics and surface pressure distribution. The numerical model developed was based on the finite volume method. A total of four cosine-shaped hills having different heights and slopes were used. The model hills were designated as S3H4, S3H7, S5H4 and S5H7, where S3 and S5 indicated the hill slope was 0.3 and 0.5 respectively, and H4 and H7 indicated that the hill height was 4 cm and 7 cm respectively. The slopes 0.3 and 0.5 were chosen to distinguish between the cases of non-separated and separated flows. In order to have a close representation of a real hilly terrain, continuous double hills made of two single hills of different shapes were investigated. A total of four double hills - (S3H4-S3H7, S3H7-S3H4, S5H4-S5H7 and S5H7-S5H4) were used and the separation distance between the back of upwind hill and foot of downwind hill was kept fixed at 5 cm.

The mean velocity characteristics for single hills S3H4 and S5H4 show that there is not any flow separation for S3H4 while as in case of S5H4, flow separation takes place. The mean velocity profile recovery occurs after 10H downstream from the hill top, both in case of S3H4 and S3H7. In case of double hill configurations, it was found that the higher hill is hardly influenced by the upwind or downwind lower hill, while the lower hill could be notably influenced by the nearby higher hill (Fig. 5). It was also seen that compared to an isolated single hill, the speed-up on the lower hill decreased by around 5% to 10%.

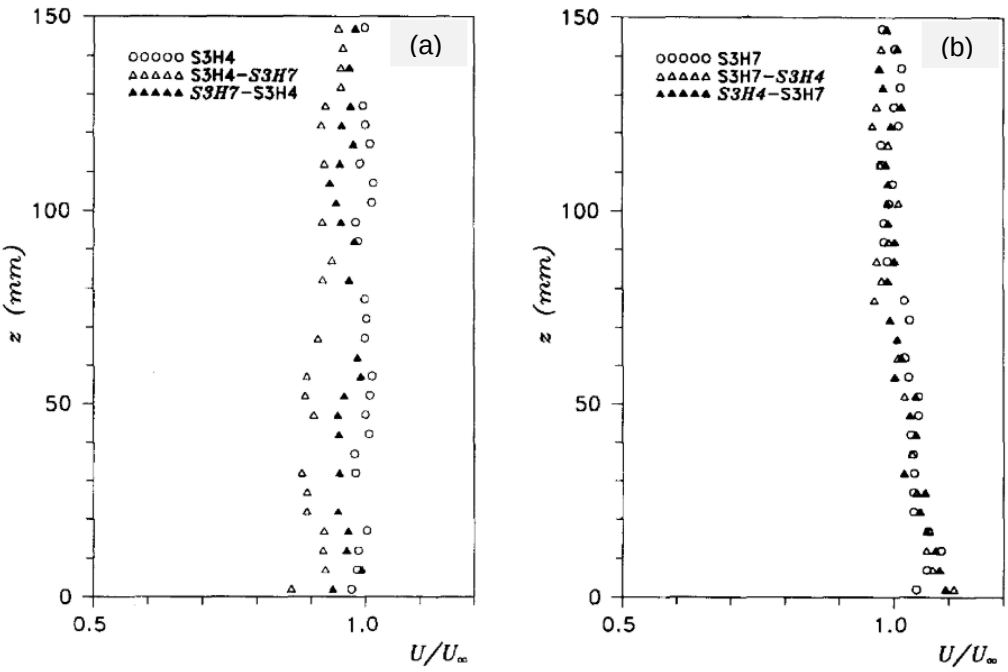


Fig. 5 Comparison of mean velocity profiles at top of the hills:
(a) S3H4 hills , (b) S3H7 hills (Kim et al., 1997)

The validation of the numerical method developed by the authors was done by comparing predictions with the experimental results. The separated flow prediction using low-Reynolds number model was acceptable and the k-ϵ turbulence model with non-orthogonal grid appeared favourable in predicting the attached flow field.

In order to quantify the effects of steep hills on the wind speed and turbulence characteristics, Carpenter and Locke (1999) carried out wind tunnel investigation of the wind flow over two-dimensional hills. The authors measured mean wind speed and longitudinal turbulence over various hill geometries viz., shallow sinusoidal hills, steep sinusoidal hills, consecutive hills and an irregularly shaped hill. Wind speeds were also calculated using Computational Fluid Dynamics (CFD) and were briefly compared with the wind tunnel results. The wind tunnel had a cross section of 1.22×2.75×5 m and the measurements were made at a scale of 1:1000. All the model hills except the half height shallow sinusoidal hill were 200 mm high. The hill configurations tested have been shown in Fig. 6. The comparatively larger size of the models was used in order to obtain Reynolds number greater than 10^5, since a considerable change in the flow conditions

takes place for Reynolds number less than 10^5 as was reported by Ferreira et al. (1991) and Ferreira et al. (1995).

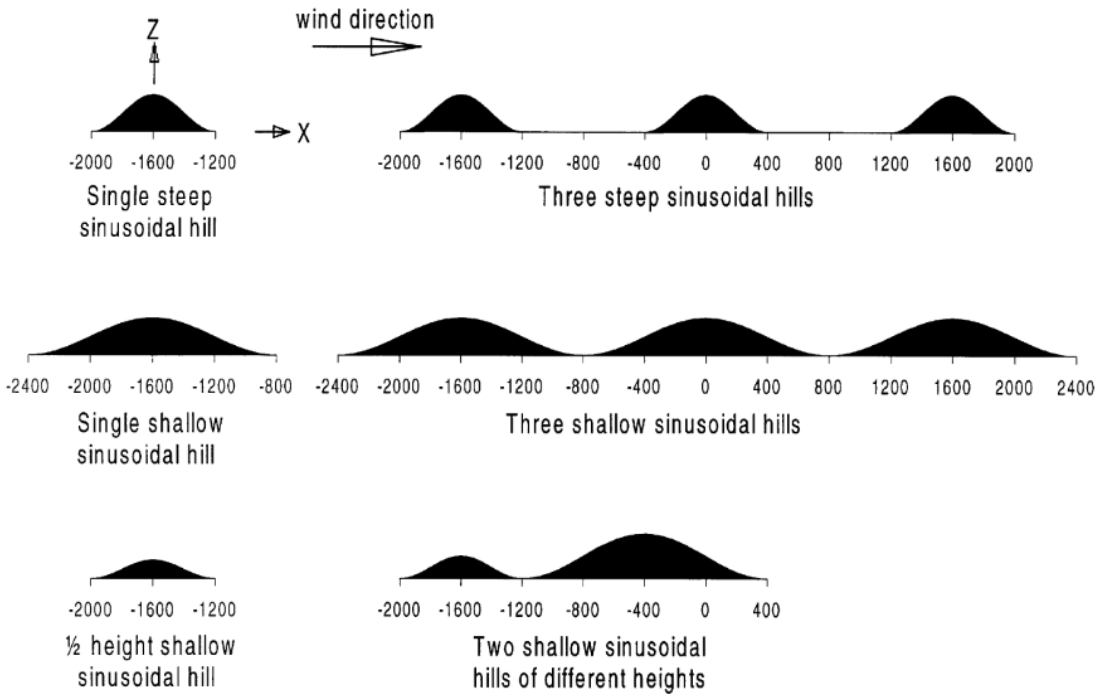


Fig. 6 Hill geometries investigated in the wind tunnel (Carpenter and Locke, 1999)

The reference mean wind speed at a height equal to the hill height (200 mm) was set to 1.0 with the other speeds scaled down relative to this value. Mean and rms wind speed profiles at the hill crest and valleys for single and multiple sinusoidal hill configurations are shown in Fig. 7. The mean wind speed above the crests is mostly constant between about 10 m and 100 m height. Compared to the shallow hills, a significant separation of the flow in the downstream region of the steep hills causes the downstream wind speed to decrease but increases the rms speed.

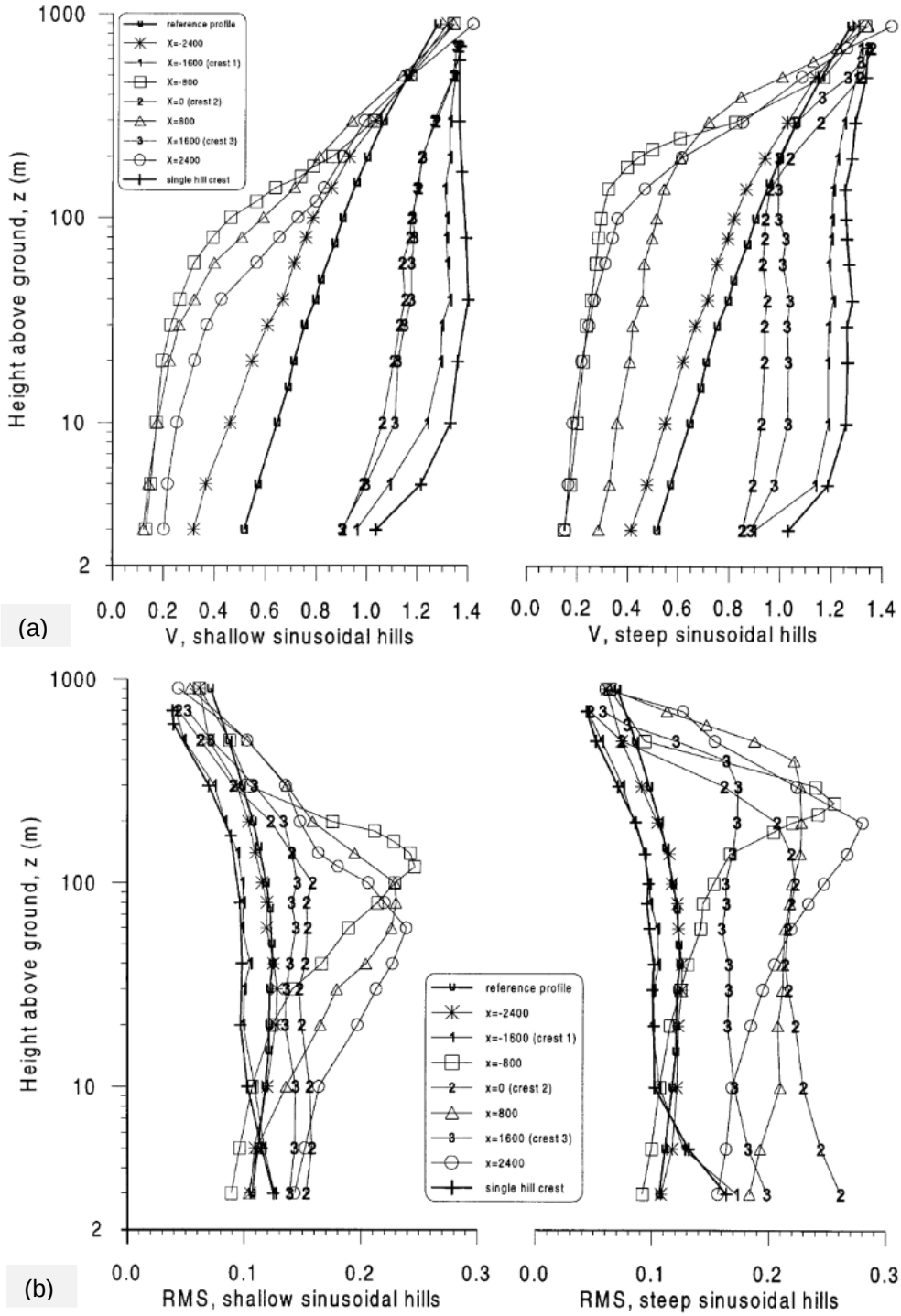


Fig. 7 (a) Mean wind speed profiles for a single hill and three consecutive hills
(b) rms wind speed profiles for a single hill and three consecutive hills
(Carpenter and Locke, 1999)

Owing to the increased turbulence at the second hill crest, the flow separation from the second hill gets reduced which increases the mean wind speed and reduces the rms wind speed at the third hill crest. The difference between the shallow and steep hills is

more noticeable at the second hill crest due to the separation behind the first steep hill. Mean wind speed and gust speed amplification factors at the hill crests were also reported. The highest amplification measured at the hill crests was 2.13 and was noticed at 5 m above the single shallow hill crest. The corresponding value for steep hill was 2.08 at 5 m height.

For measuring the effect of irregularities in the hill profile, five step configurations were formed on the upwind slope of the single sinusoidal hill and the effect of each configuration on the wind flow was tested. The height and position of the steps influenced the wind flow over the hill. It was observed that the 20 m high step which was 200 m upstream of the crest had the highest impact on the wind profiles at the crest. The mean speed was reduced to half and the rms speed increased by a factor of 1.5, both below 10 m height. Another observation that the authors made was the pronounced effect that the relatively small irregularity (5 m step located 100 m upstream of the hill crest) can have on the flow. Numerical simulations of the flow were compared with the wind tunnel investigation results. Mean wind speeds calculated were fairly comparable with the wind tunnel results for geometries where the flow separation was very little. RMS wind speeds showed poor agreement between the wind tunnel and CFD results.

Cao and Tamura (2006) investigated experimentally the surface roughness effects on the boundary layer flow over a steep hill. The wind tunnel was an open circuit type and had a cross section of 0.8×1×7 m. The model hills considered were cosine shaped and had a height (H) of 40 mm and a length (L) of 100 mm. Figure 8 shows the experimental set-up taken by the authors. The maximum slope of the hill shape considered was around 32˚ on the leeward side, which was greater than the critical value (about 16˚) as suggested by Finnigan (1988) for the flow separation to take place.

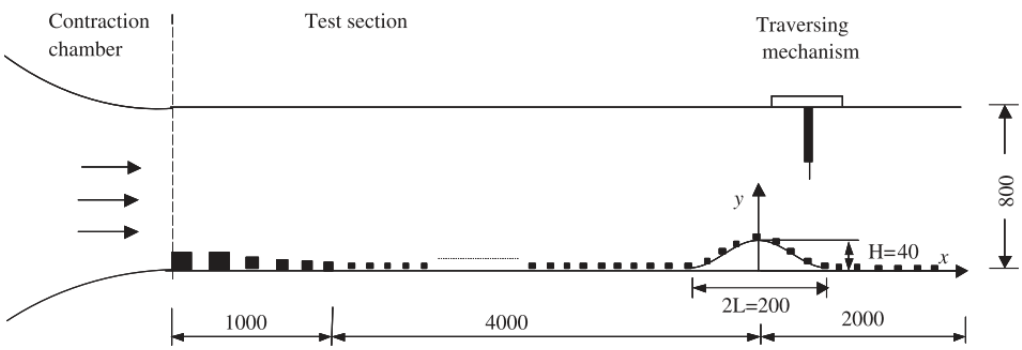


Fig. 8 Experimental set-up investigated (Cao and Tamura, 2006)

The authors carried out an experimental study of turbulent boundary layer over smooth and rough steep hills, with the focus mainly on the impact of surface roughness on the speed-up ratio and the behavior of the separation bubble. Mean velocity profiles and turbulence intensity profiles, power spectrum and the turbulence structure over the hill were presented and compared with those of oncoming turbulence on a flat plate to recognize the effects of surface roughness. Additionally, the comparison between the flow over smooth and rough hills was also made. The rough surface conditions were modeled by placing small sized cubes on the surface of the hill. Reynolds number (R_e)

difference between the two surface conditions was not large enough to take into consideration its effects. The profiles of longitudinal mean velocity at different downstream locations for the smooth and rough surface hills are shown in Fig. 9. Longitudinal mean velocity was normalized by the free- stream velocity (U_∞). A deceleration in the flow was observed at the upwind hill foot and an acceleration was seen at the crest. The mean velocity profiles on the leeward side of the hill were entirely different from those on the upstream side owing to the flow reversal, or the separation bubble on the leeward side. It could also be observed that the turbulent property was affected by the hill within a long downstream region which was reflected in the mean velocity profiles recovery (to its actual state) as in the upstream flow. A significant deviation on the leeward side of the rms value of the longitudinal velocity fluctuation σ_u was observed, with increased values at nearly the hill height owing to the separated shear layer (Fig. 10).

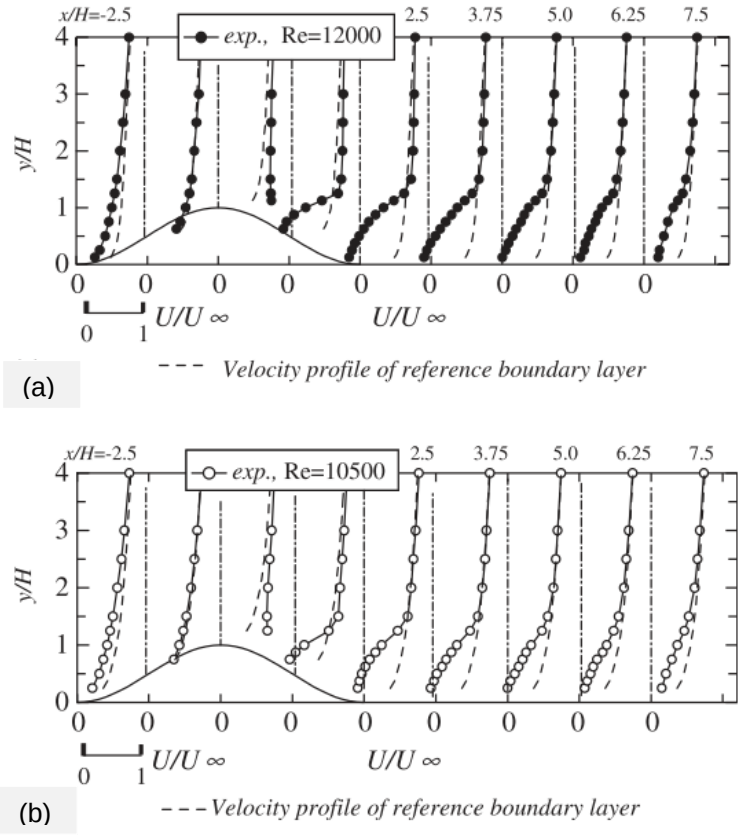


Fig. 9 Mean velocity profiles over (a) Smooth hill surface and (b) Rough hill surface (Cao and Tamura, 2006)

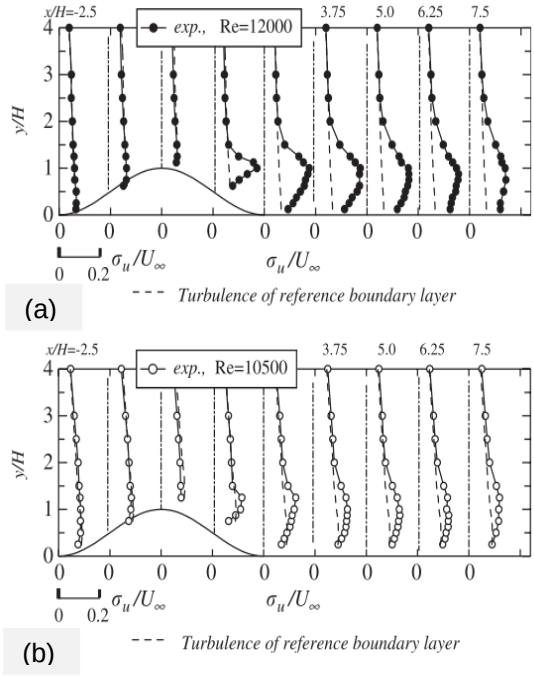


Fig. 10 Turbulent intensity profiles over (a) Smooth hill surface and (b) Rough hill surface (Cao and Tamura, 2006)

To predict the influence of topography on the design wind speed, it is generally agreeable to take into consideration the mean wind velocity increase over the hill with the help of a parameter known as fractional speed-up ratio. The authors made an important observation that in case of a steep hill, rough upstream conditions cause the speed-up ratio to be greater than the smooth upstream conditions, and the roughness of the hill surface reduces the speed-up ratio if the upstream conditions are similar.

The turbulent statistics in the wake were studied and the reattachment length of the rough hill was found to be larger. The reverse flow intermittency defined as the time interval during which the flow at a given position is in reversal, at a given point of the rough hill was observed to be greater than that of the smooth hill and the difference between the two became evidently larger moving close to the ground. In order to investigate the vortex behavior on the leeward side of the hill, spectral analysis was carried out on the longitudinal velocity fluctuations in the wake of the hill. Compared with the inflow turbulence at the low normalized frequency number, the power spectrum of the rough hill showed a greater decrease than that of the smooth hill. To conclude this study, it could be pointed out that the results shown were an amalgam of the roughness block effects on the surface of the hill and on the upstream ground surface. The rough condition of the upstream ground surface governed the upstream turbulence characteristics which indeed played a vital role in the variation of turbulent boundary layer flow over the hill.

Cao and Tamura (2007) studied experimentally the effects of roughness blocks on the turbulent boundary layer flow over a low hill which had the maximum slope of 0.21 and did not accompany stable separation. Among other studies lately on the flow over

two dimensional hills, Li et al. (2017) investigated the flow field characteristics in the atmospherics boundary layer flow over multiple hill and valley configurations under neutral conditions. The experimental investigation carried out by the authors provided a finer understanding of the wind energy distribution on the terrain for appropriate selection of sites for the installation of wind farms in the atmospheric boundary layer.

3. EXPERIMENTAL INVESTIGATION ON ESCARPMENTS

The research on the wind flow over two-dimensional escarpments has lately been scarce. One of the prominent studies carried out dates back to 1970's when Bowen and Lindley (1977) studied experimentally the wind speed and turbulence characteristics over various escarpment shapes.

Tsai and Shiau (2011) conducted wind tunnel experiments to measure the wind flow and turbulence characteristics over an upwind escarpment with slope 15˚. The wind tunnel had a cross section of 2×1.4×12.6 m. The height H of the model was 13.4 cm and the horizontal length (L) of the upwind slope was 50 cm. The experimental set-up and measurement coordinates are shown in Fig. 11. The 15˚ slope was chosen in order to avoid the flow separation along the upwind slope surface and the top surface of the escarpment model. The Reynolds number effect was neglected in the study since the value of it came out to be greater than the critical value.

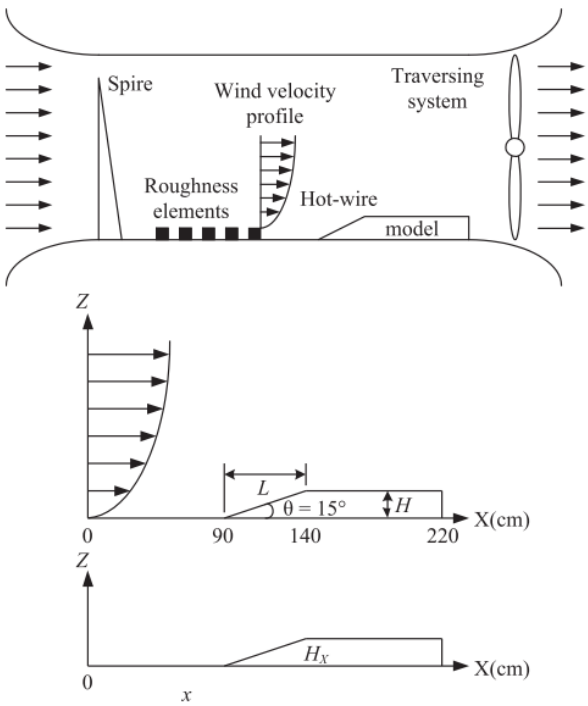
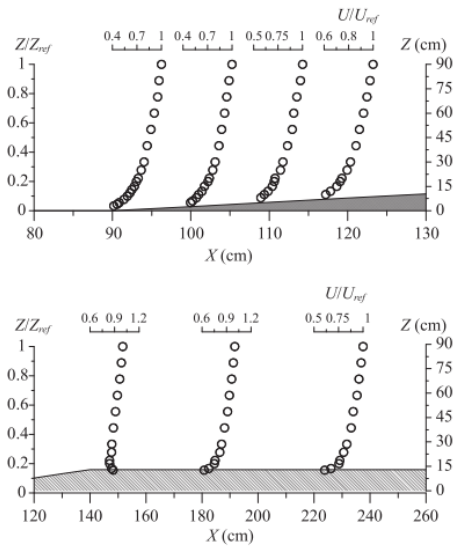


Fig. 11 Experimental arrangement used in the study (Tsai and Shiau, 2011)

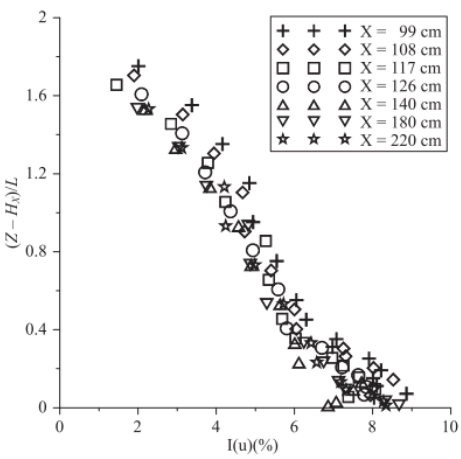
The mean velocity profiles were measured at different strategic locations (x = 99 cm, 108 cm, 117 cm, 126 cm, 140 cm, 180 cm and 220 cm). These are shown in Fig.12. The flow separation did not take place when the wind flow was beyond the upwind slope of the escarpment. As compared to the approaching flow, the wind speed increased dramatically near the tip of the escarpment slope (x = 140 cm).



Z_{ref} is the boundary layer thickness and U_{ref} is the free stream velocity

Fig. 12 Mean velocity profiles at various locations of the escarpment model (Tsai and Shiau, 2011)

The longitudinal turbulence intensity I(u) profile for different downstream locations is shown in Fig. 13. It was observed that the turbulence intensity decreased from the toe of slope (x = 99 cm) to the tip of slope (x = 140 cm).



H_x is the height of escarpment where the downstream distance is x

Fig. 13 Longitudinal turbulence intensity profiles at different locations for wind flow over escarpment slope (Tsai and Shiau, 2011)

The authors also studied the wind power spectrum for various sites along the slope and demonstrated that the usual governing spectrum peak that is representative of the vortex-shedding frequency mostly occurring for bluff body or flow separation was absent as wind flow took place over the upwind slope and top surface of escarpment. This result was conclusive enough to say that the flow separation does not take place when the wind flows over the 15˚slope escarpment.

4. CONCLUSIONS

An entire spectra of applications makes it important to study the wind flow over a hilly terrain. This review of wind flow over two-dimensional hills and escarpments has attempted to summarize the results derived from the wind tunnel experiments over the past three decades. The paper summarizes the research developments in the area of wind flow over hilly terrains with focus on wind tunnel investigations on two-dimensional features. The data and results available are mostly confined to the wind speed profiles, turbulence characteristics and pressure distributions. The studies cannot be compared directly because of the different hill and escarpment configurations, the wind tunnel set-ups and the flow conditions used. However, it is concluded from the review presented herein that there is a need to carry out more experimental investigations on the escarpments in order to have comparable data on the wind flow characteristics so that more precise recommendations for the wind flow characteristics over a hilly terrain can be given.

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