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Comparative Wind Tunnel Analysis of Wind Flow Characteristics over Gentle and Steep Escarpment Slopes

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Abstract

Wind flow dynamics play a crucial role in a range of engineering applications, such as optimizing wind farm site selection for efficient energy distribution, analysing forest fire spread, and evaluating wind loads on structures in mountainous regions. This study provides a comparative analysis of wind flow characteristics over two-dimensional escarpments with gentle (15°) and steep (75°) slopes, based on experimental investigations conducted in a boundary layer wind tunnel. An extensive wind flow characteristics study is carried out for the two escarpment models which span the entire width of the wind tunnel (two-dimensional). Results measured include mean wind velocity profiles and turbulence intensity profiles across the terrain length at a total of 17 locations. The analysis highlights the impact of slope on wind flow patterns, turbulence intensities, and amplification factors, offering valuable insights into topographical influences on wind behaviour. The findings presented in this paper are significant for applications in structural safety and wind energy. Based on the results of this paper, the authors also recommend the strategic locations for buildings to be built in hilly terrains.

Keywords

Wind Tunnel; Two-dimensional Escarpment; Flow characteristics; Comparative analysis; Structural safety

1. Introduction

Wind loading is one of the most sophisticated requirements for the building design. Buildings must be properly designed in order to accommodate for the most severe design scenarios that might arise within a certain design period. This requires accurately estimating the impacts of turbulent wind forces. The effect of wind on a building is primarily determined by the building's shape, height, and location. Wind loads on a building can cause structural damage and can also result in damage to cladding and other non-structural components. Therefore, it is important to accurately determine the wind loads acting on a building to ensure that the structure is able to withstand the imposed loads and thereby creating a safe and secure environment for the occupants. The modern approach to understand wind flow in hilly terrains started back in early 1970's. Studies in the recent two decades include the work of Cao and Tamura (2006), Cheynet et al., (2016), Hyvärinen et al., (2018), Pirooz and Flay (2018), Sharma et al., (2021), Wani et al., (2024). In order to accurately determine localized wind speed and direction in hilly terrains, it is essential to understand how abrupt changes in topography modify the atmospheric boundary layer (Bowen and Lindley, 1977). Understanding wind flow over complex terrains is essential for a wide range of engineering and environmental applications, including wind energy generation, structural safety, pollutant dispersion, and microclimate design. Jensen and Peterson (1978) used the results from theories for flow over low-ridges to gauge the features of wind profile downwind of an escarpment (investigated the air flow along a small coastal escarpment from the sea to the land). Jensen (1983) in his study compared surface-layer wind profiles of sloping escarpment with Jackson and Hunt's analytical theory (Jackson and Hunt, 1975) and concluded that the theory does not succeed in predicting correctly the vertical and downwind variation of the velocity fluctuations. Among the notable field studies on wind flow over escarpments, the work of Emeis et al., (1995) stands tall. It is fair enough to say that wind flow on escarpments have received less attention compared to wind flow on hills, particularly in early 2000's. Studies in the last two decades include the work of Sherry et al., (2010), Lange et al., (2016), and Kilpatrick et al., (2021). Several studies have explored structural performance under various extreme loading conditions such as seismic or wind loads (Yousef et al., 2024). Recent studies which investigated flow in complex terrains experimentally and/or numerically, with varied applications, include the work of Letson et al., (2019), Tabas et al., (2019), El Bahlouli et al., (2020), Finnigan et al., (2020), Cai et al., (2021), Hesp and Smyth, (2021), Weicheng et al., (2021), Wenz et al., (2022), Dar and Porté-Agel, (2022), Sun et al., (2023), Davalos et al., (2023), and Shen et al., (2025) . Other recent studies include the work of Dar and Porté-Agel (2024) where they investigated the wake behind a wind turbine placed on an escarpment, and Wani et al., (2023) where they carried out wind tunnel investigation on a two-dimensional escarpment focusing on assessing the topographic factor.

Escarpments, which are abrupt changes in topography, play a critical role in modifying wind flow patterns. The slope of the escarpment significantly influences the behaviour of wind, leading to phenomena such as flow acceleration, separation, recirculation, and turbulence (Fig. 1 and 2). Gentle slopes tend to allow for smoother flow transitions but may still exhibit critical changes in wind speed and turbulence intensity. Steep escarpments, on the other hand, often cause pronounced flow separation and create zones of high turbulence and recirculation, which can impact structures and ecosystems downstream. Previous studies have focused on isolated cases of wind flow over gentle or steep escarpments, but a direct exhaustive comparative analysis of these effects remains limited.

This study aims to fill this gap by examining the wind flow characteristics over two-dimensional escarpments with gentle (15°) and steep (75°) slopes. The experimental investigations focus on analysing the mean wind velocity and turbulence intensity under controlled wind tunnel conditions. This work aims to provide a deeper understanding of the role of slope in shaping wind behaviour and its implications for engineering and environmental applications.

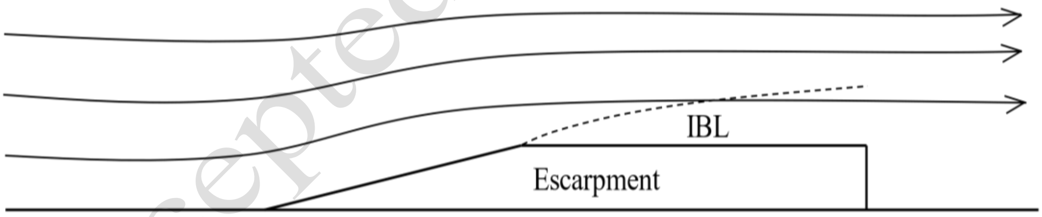

Fig. Error! No text of specified style in document.**:** Typical flow over an escarpment with gentle slope and formation of internal boundary layer (IBL)

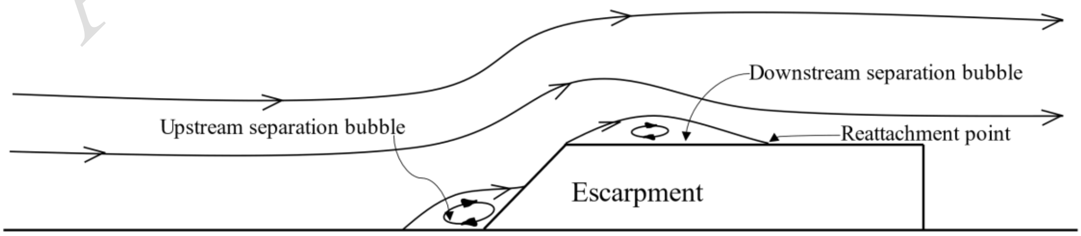

Fig. 2: Typical flow over an escarpment accompanied with flow separation

2. Methods

2.1 Wind Tunnel and Flow Characteristics

The experiments are conducted in an open-circuit boundary layer wind tunnel at IIT Roorkee (India), with a test section measuring 15 m in length and cross-sectional area of 2 m × 2 m (Fig. 3). Vortex generators and barrier walls are employed to simulate the atmospheric boundary layer. The free-stream velocities are close to 10.3 m/s (at 900 mm boundary layer depth), with a power-law exponent of 0.2 for both cases. Maximum turbulence intensity near the wind tunnel floor is around 14% in the empty tunnel conditions. The approach-flow mean wind velocity and turbulence intensity profiles for the undisturbed flow case (UFC) are depicted in Fig. 4.

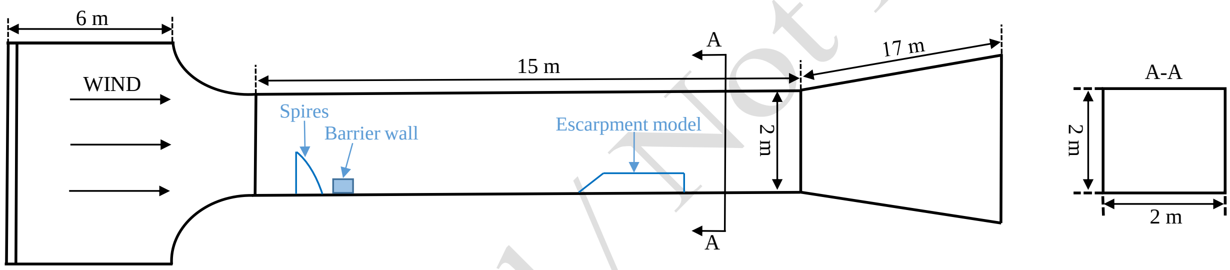

Fig. 3: Schematic diagram of the open-circuit boundary layer wind tunnel (not to scale)

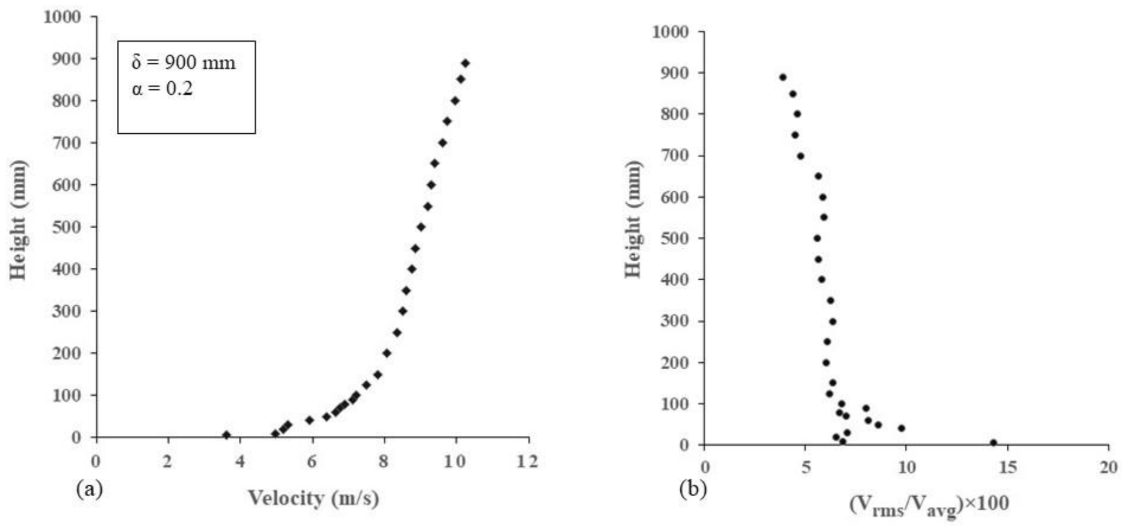

Fig. 4: Wind flow characteristics without the presence of escarpment (flat terrain/undisturbed flow case); (a) Mean wind velocity profile, (b) Turbulence intensity profile

2.2 Model Details

A total of two models spanning the entire width of the wind tunnel (two-dimensional) are fabricated using plywood. The first model has a gentle slope of 15° and the second model has a steep slope of 75° (Fig. 5). The height of both the models is kept fixed at 300 mm. A geometric length scale of 1:100 is adopted throughout the study, thereby maintaining a similarity all through the experimentation. While Reynolds number scaling can influence absolute velocity magnitudes, prior research has shown that the dominant flow phenomena in separated flows over escarpments are largely Reynolds number independent beyond a critical threshold (Ferreira et al., (1991, 1995)). Thus, the observed trends remain applicable to full-scale conditions. Measurements are taken at 6 upstream and 11 downstream locations for both slopes, covering strategic points to capture variations in mean wind velocity and turbulence intensity.

2.3 Measurement Technique

Mean wind velocity and turbulence intensity for the flat terrain/UFC are measured using a high-precision digital air flow meter instrument named Testo 480 which is equipped with a vane probe that has four vanes measuring 16 mm in diameter (Fig. 6). The instrument can measure flow velocities up to 50 m/s and has a minimum resolution of 0.1 m/s. The Testo 480 device is interfaced with a computer to facilitate real-time wind velocity measurements. Real-time wind velocity measurements are recorded using Testo Easy Climate software (v3.4).

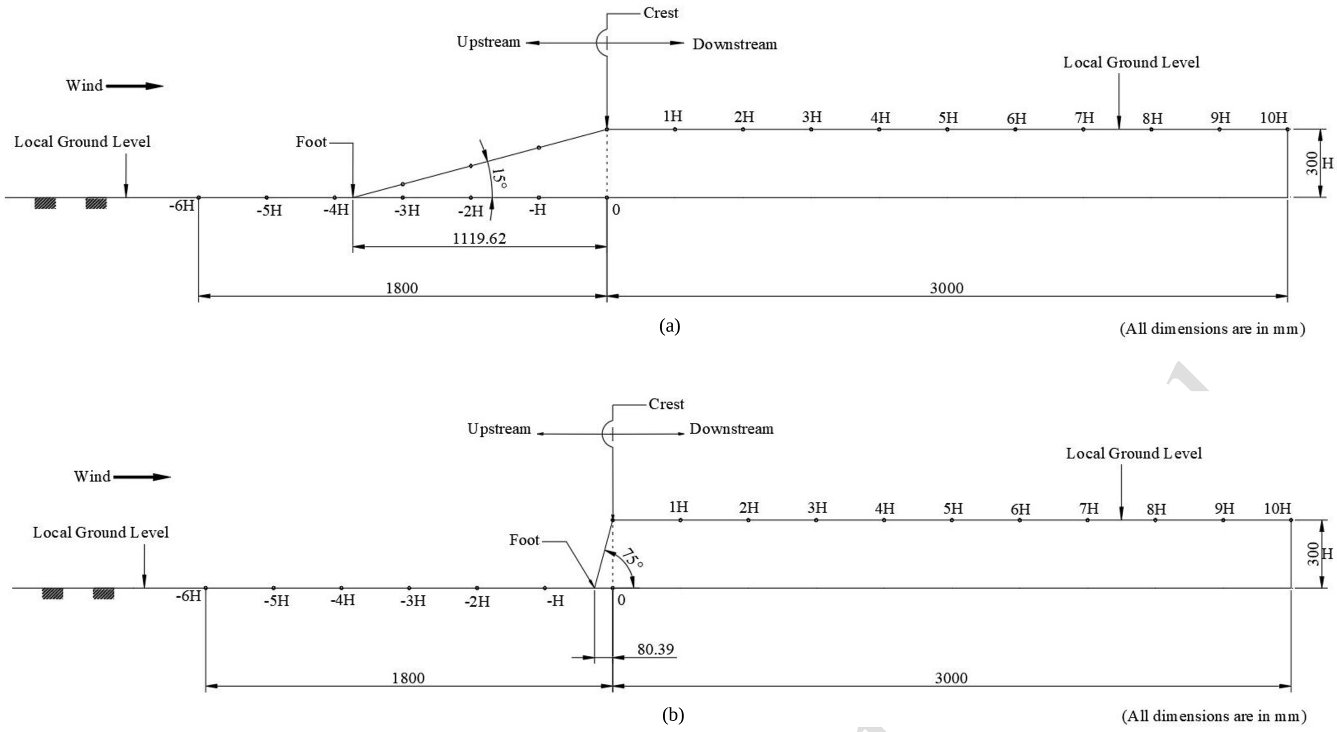

Fig. 5: Cross-sectional diagrams of the two escarpment models illustrating the strategic measuring locations; (a) 15° slope, (b) 75°slope

(a) **(b)**

Fig. 6: (a) Testo-480 with flow velocity displayed, (b) Vane probe

3. Results and Discussions

3.1 Mean Wind Velocity

Mean wind flow is measured over the two escarpments at successive locations between 6H u/s and 10H d/s. The velocity profiles at a few selected locations for both the escarpments are shown in figure 7. The mean wind velocity profiles at the reference section (UFC) and 6H u/s are almost similar for both the escarpments, which indicates that due to the presence of escarpments, there is no significant change in the flow characteristics at 6H u/s. A common observation for both the escarpments is the reduction in mean wind velocity when the flow approaches the upstream foot of each escarpment (4H u/s for 15° slope and 1H u/s for 75° slope). This observation was also noted by Pearse (1982) for the conical hills which were investigated in a wind tunnel. An interesting observation depicted in figure 7 is that in case of 15° escarpment, where the upstream foot is just close to 4H, no flow separation is observed as the flow remains attached to the escarpment surface. In case of 75° escarpment, where the upstream foot is just near 1H, flow separation is clearly observed as there is a small region of flow reversal (Fig. 7 (d)) with an approximate height equal to H/10. This region of flow reversal is also referred to as a 'separation bubble' which is mostly characterized by reduced mean wind velocity and high turbulence intensity. Flow separation generally occurs due to an adverse pressure gradient and is normally seen in slopes greater than the critical slope of 17°, as reported by Finnigan (1988). Figure 2 shows the typical flow over an escarpment accompanied by flow separation. Flow acceleration over the sloping portion is evident for both the escarpments, in particular for 15° escarpment, where a more pronounced and rapid acceleration is seen in the lower region of flow at 2H u/s and 1H u/s. A clear reason for this distinctive behaviour in velocity distribution is attributed to absence of flow separation in case of 15° escarpment. Since the flow remains attached to the surface of 15° escarpment (gently sloped), more pronounced acceleration is seen compared to the small region of flow reversal in case of 75° escarpment. The incoming flow gets separated close to 1H u/s location in case of 75° escarpment.

Wind speed-up is observed at the crest, for both escarpments, with the increase in mean wind velocity being confined to one escarpment height above the local ground level (Fig. 7 (e)). It is observed that the amplification in the mean wind velocity is greater for 15° escarpment compared to 75° escarpment. Beyond the crest, an escarpment presents an elevated feature above the normal ground level due to which the velocity profile is always different compared to the undisturbed flow until the downstream recovery of the velocity takes place. Observing for 15° escarpment, at 1H d/s, which is just near the crest, rapid acceleration of flow is seen in the lower portion. This is due to the wind speed-up effect persisting close to the crest but up to one escarpment height only (above the local ground level). An interesting observation which can be made from the profiles downstream of the crest, i.e., 1H d/s till 10H d/s, is that there is little or no variation in the velocity along the height measured above the local ground level, which suggests that an internal boundary layer is developed beyond the crest in the downstream direction confined to the lower portion of the flow.

In case of 75° escarpment, beyond the crest, at 1H d/s and 2H d/s, small regions of flow reversal are seen owing to the downstream separation. The size of the region of recirculation of flow is confined to H/3, with the size getting reduced from 1H d/s to 2H d/s. Beyond 2H d/s, from 3H d/s till 10H d/s, a rapid acceleration of flow is seen, which mostly, is confined in the lower portion of the flow. This height above the local ground level where the flow accelerates is approximately equal to H/1.2. A key observation here is the presence of a separation bubble, which significantly influences the flow reattachment process. This phenomenon results in heightened turbulence intensities near the crest and downstream zones, with implications for structural loading and pollutant dispersion. In contrast, the gentle slope allows for smooth flow acceleration along the slope without any observable separation. The wind speed gradually increases from 3H upstream to the crest, reaching a maximum value. Unlike the steep slope, the flow over the gentle slope exhibits a more uniform velocity profile, with reduced turbulence intensity. Although no separation was observed for the gentle slope, the acceleration of the flow along the slope generated high turbulence at 1H upstream. This turbulence dissipated more rapidly compared to the steep slope, highlighting the role of slope gradient in modulating turbulence decay.

It is important to quantify the above mean wind velocity variations for both escarpments slopes, with respect to the velocity profile for undisturbed flow case shown in figure 4. The comparative values in terms of percentage differences at some key locations are given in Table 1, for 15° and 75° escarpments, respectively. It is to be noted that the negative sign denotes percentage decrease.

Table 1: Percentage variation of mean wind velocity profiles (in comparison with UFC profile) for the two slopes at selected key locations

Location	Slope	Slope
	15°	**75°**
2H U/S	7%	-22%
1H U/S	18%	-39%
Crest	35%	44%
1H D/S	34%	10%
4H D/S	24%	11%

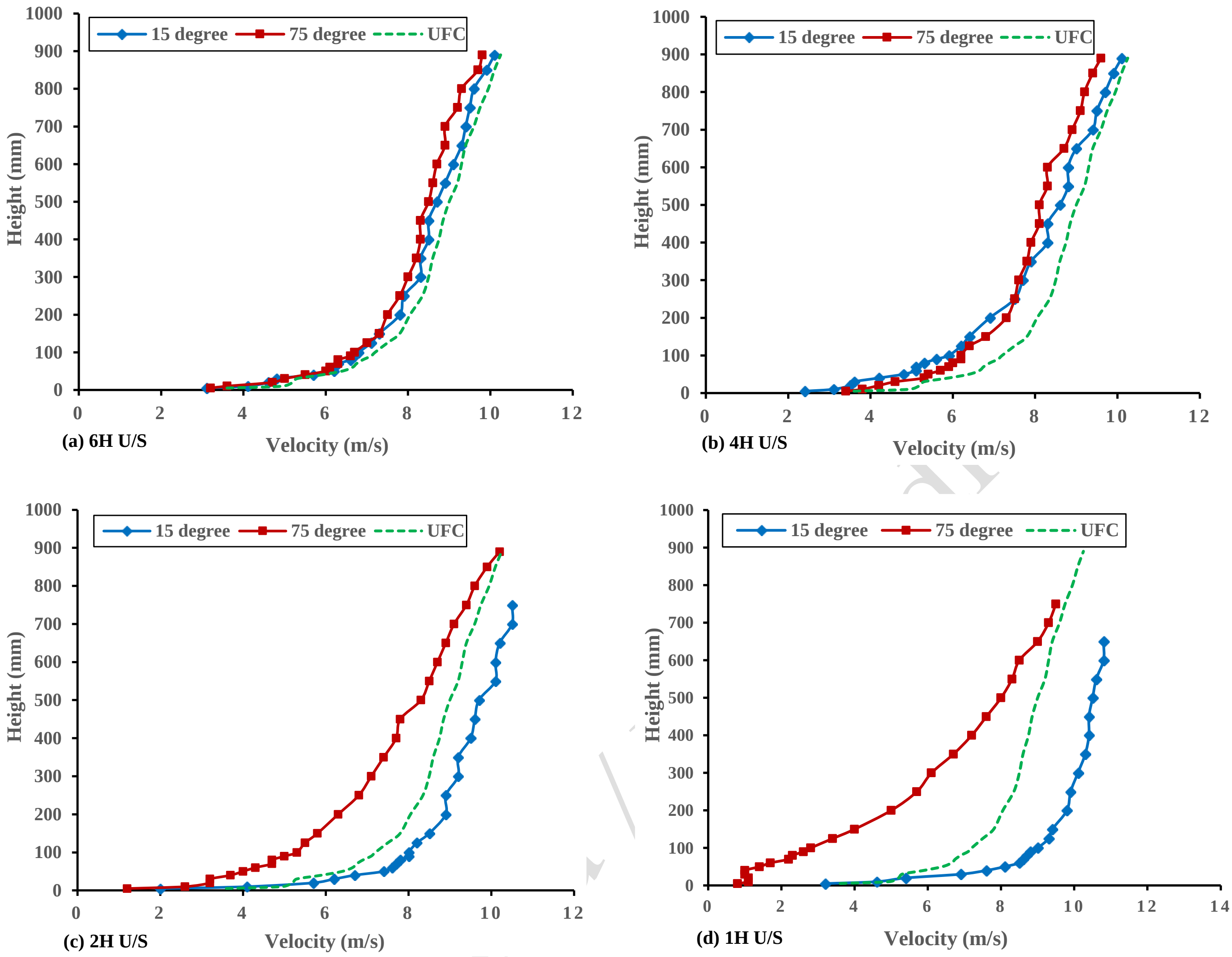

Fig. 7: (a)-(j) Mean wind velocity variation at a few selected locations for both the escarpment slopes (contd…)

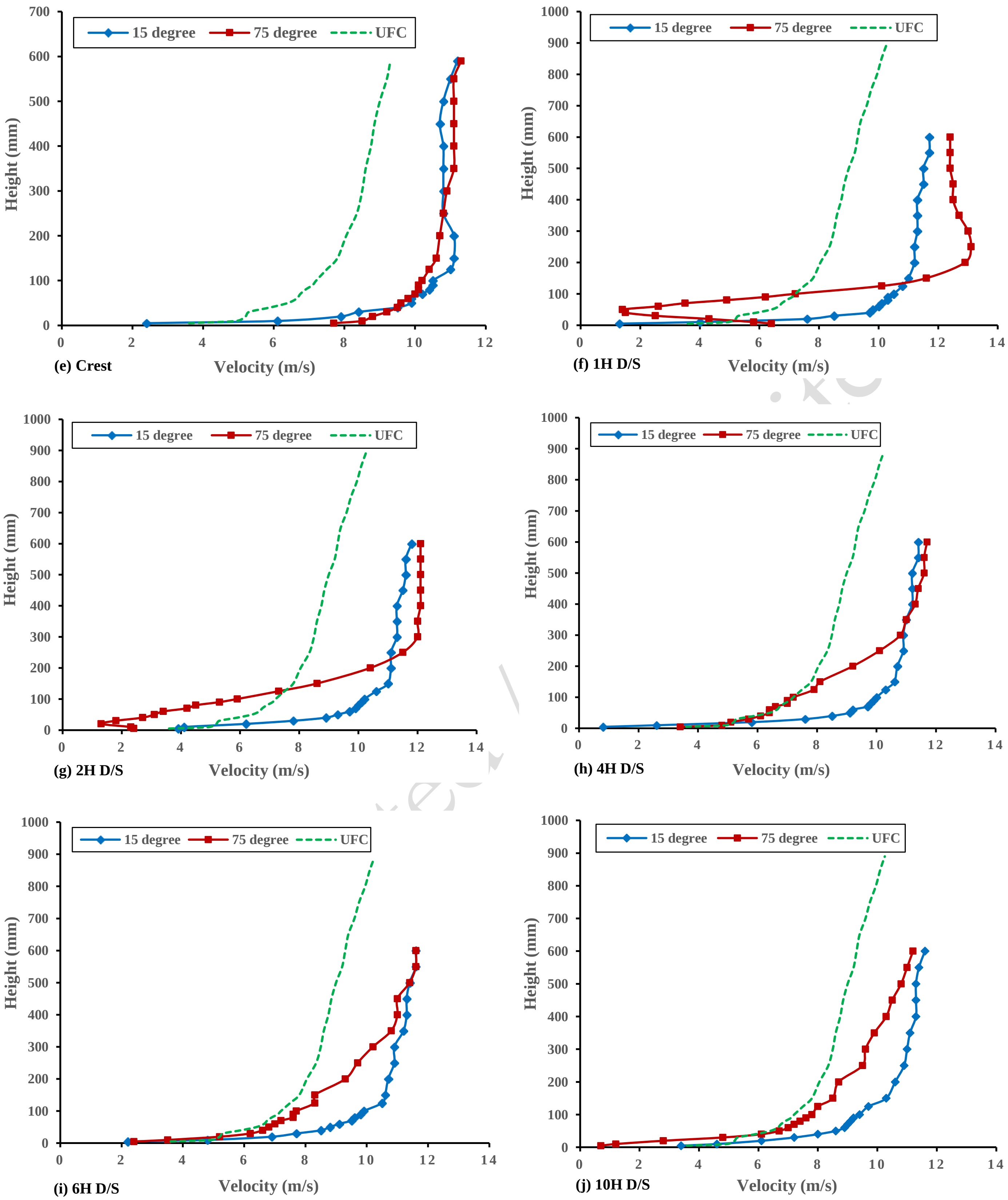
15 degree
75 degree
UFC
Height (mm)
Velocity (m/s)
(e) Crest
(f) 1H D/S
(g) 2H D/S
(h) 4H D/S
(i) 6H D/S
(j) 10H D/S

Fig. 7: (contd…)

3.2 Turbulence Intensity

Turbulence intensity profiles for a few selected locations are shown in figure 8. Observing for 15° escarpment, turbulence intensity of around 22% in the lower region of flow is seen at 4H u/s. At 1H u/s, the turbulence intensity values ranging between 13% and 26% are seen up to a height of 20 mm from the local ground level. Beyond this 20 mm height, the turbulence structure does not vary significantly with the height. Due to the increased mean wind velocity at the crest, also known as the wind speed-up, the turbulence intensity reported in the lower region of flow is low, around 10%. The value at the lowest measuring point (5 mm from the local ground level) is around 25%, at the crest. The reason for this increased value could be the lowest mean wind velocity at this 5 mm height (Figure 7 (e)). At 10H d/s, which is the last measuring location, a maximum value of around 22% is seen at 5 mm height from the local ground level.

In case of 75° escarpment, low turbulence intensity of around 7% in the lower region of flow is seen at 4H u/s. At 1H u/s, the maximum turbulence intensity of around 37% is seen at a height of 40 mm from the local ground level. At crest, the maximum turbulence intensity reported in the lower region of flow is around 27% and it keeps decreasing until the height of 200 mm (from the local ground level) is reached, where from it does not change much and remains constant. Beyond 3H downstream, the flow began to stabilize but retained some residual turbulence, indicating incomplete recovery even at 10H downstream. At 10H d/s, which is the last measuring location, a maximum value of around 30% is seen at 20 mm height from the local ground level.

Comparing the two slopes and ascertaining the effect of escarpment slope, it could be fairly argued that the smoother gradient (15° escarpment) facilitates a more gradual energy dissipation, which could influence pollutant dispersion and wind energy harvesting efficiency. For the steeper slope, the turbulence extends from 1H upstream to 2H downstream, forming a localized zone of high-energy fluctuations. These characteristics are critical for evaluating wind-induced dynamic effects on structures situated in such terrains.

It is a well-established fact that surface roughness can alter the flow characteristics in a flat as well as a complex terrain. Surface roughness can significantly influence boundary layer development, turbulence intensity, and flow separation behaviour, particularly in a complex terrain. In our study, we used a smooth surface to isolate the effects of slope variations on wind velocity and turbulence intensity. While this approach provides a fundamental understanding of flow behaviour over escarpments, real-world terrain features often exhibit varying roughness, which can modify velocity profiles and affect the extent of flow separation and reattachment. Increased roughness could lead to earlier turbulence generation, higher aerodynamic drag, and modified wind load distributions on structures.

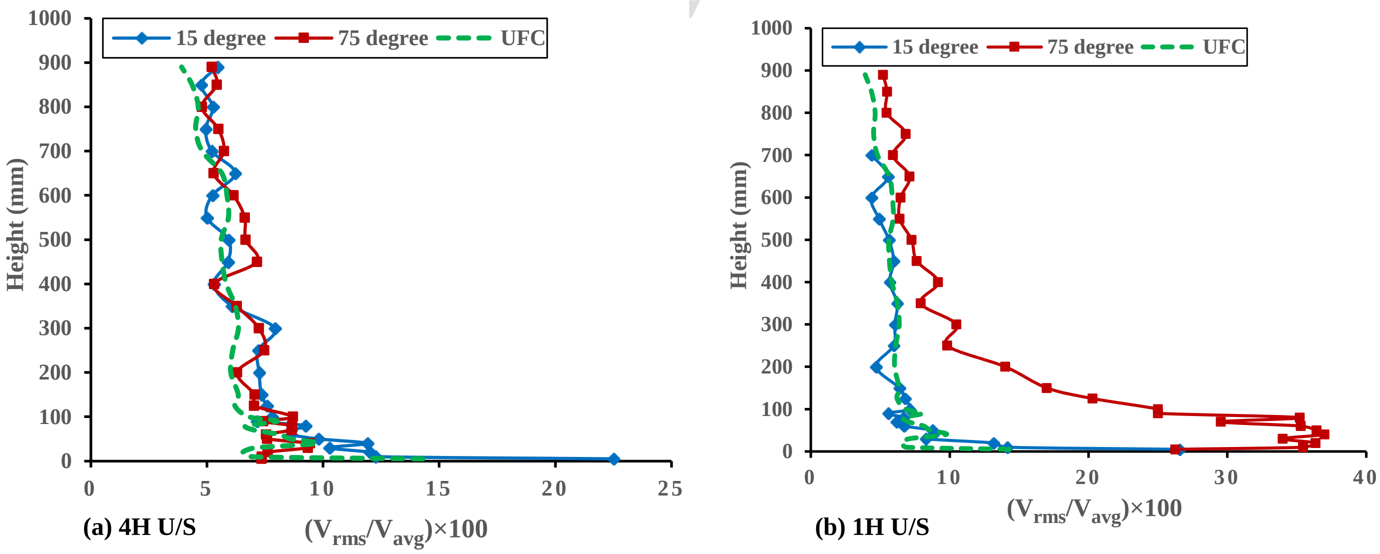

Fig. 8: (a-f) Turbulence intensity profiles at a few selected locations for the two escarpment slopes (contd…)

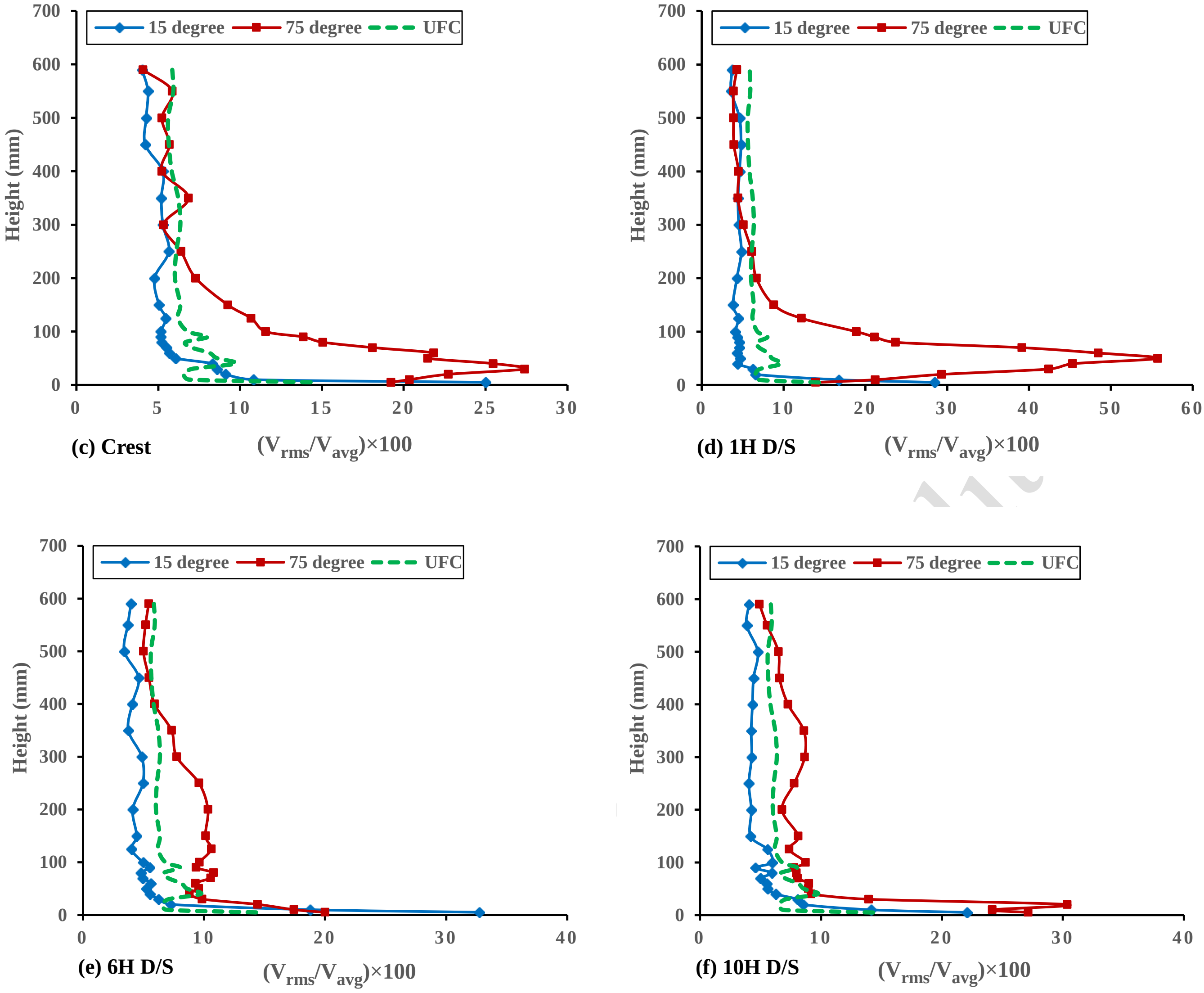

Fig. 8: contd…

3.3 Wind velocity variation along terrain length

Figure 9 shows the mean wind velocity variation along the terrain length (6H u/s to 10H d/s) for the two escarpment slopes at selected heights. The heights chosen are 30 mm (H/10), 100 mm (H/3), 300 mm (H), and 600 mm (2H), from the local ground level. An interesting observation is that for the steeper slope, at lower heights of 30 mm and 100 mm, there is a drastic variation in the wind velocity between 2H u/s and 3H d/s. This is due to the pronounced flow separation in the steeper slope escarpment from 2H u/s till

3H d/s. Figure 9 also depicts the flow recirculation regions, also known as a separation bubble, which is characterized by high turbulence intensity and reduced mean wind velocity. In contrast, the gentle slope escarpment, except for the smaller heights (30 mm and 100 mm), presents a steady variation of wind velocity along the terrain length.

The comparative results indicate that steep slopes are prone to creating localized zones of high turbulence and amplified wind speeds, which must be carefully accounted for in structural design and site selection for wind energy projects. In contrast, gentle slopes offer a more stable wind profile but may result in lower wind energy potential.

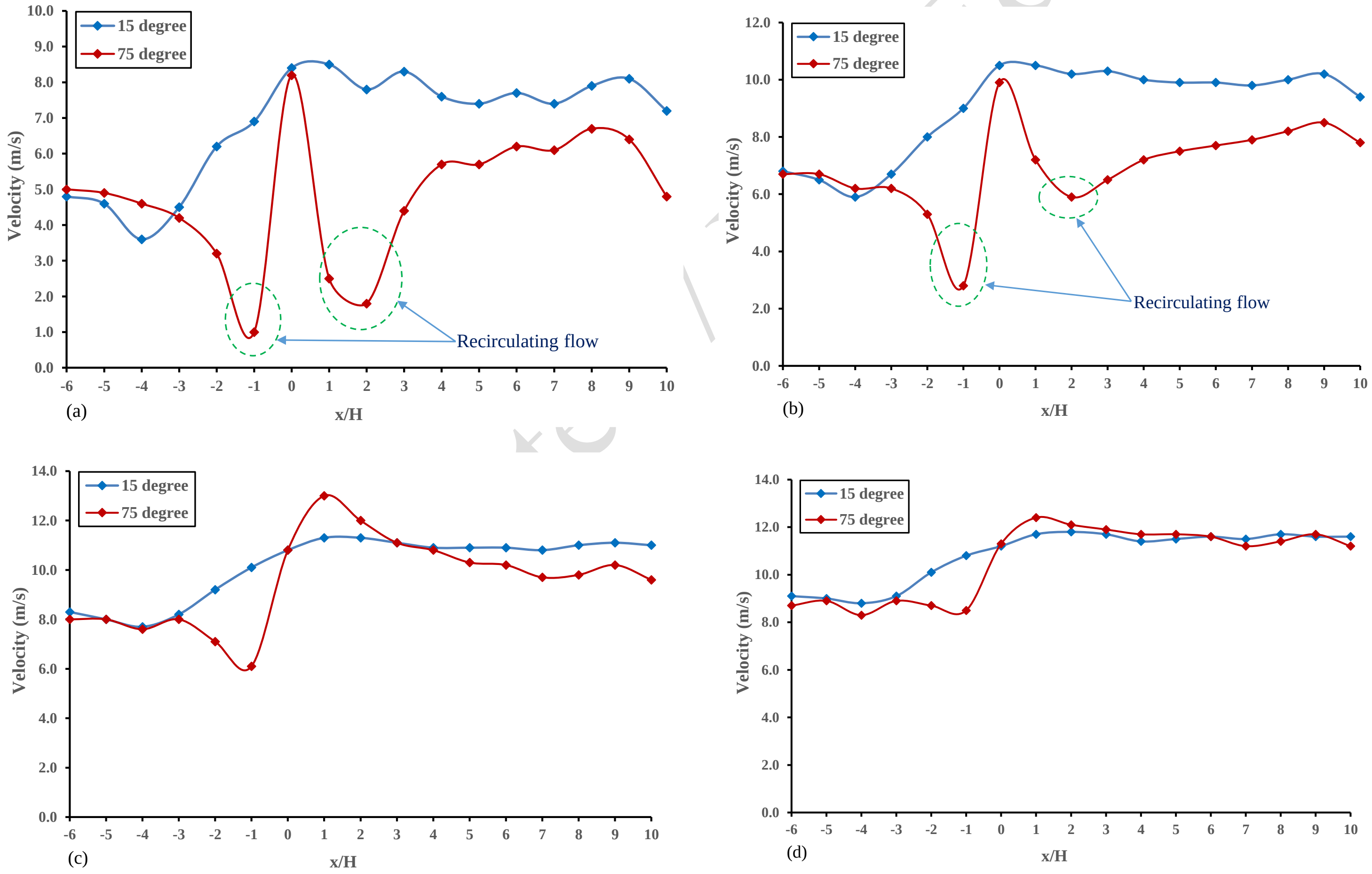

Fig. 9: Wind velocity variation along the terrain length at a few selected heights from the tunnel floor; (a) H/10, (b) H/3, (c) H, (d) 2H

4. Conclusions

This wind tunnel study highlights the significant influence of escarpment slope on wind flow characteristics. The findings of this paper underscore the importance of considering escarpment slope in wind engineering applications, particularly for site-specific assessments in hilly terrains.

The conclusions that stem from the study are:

- The effect of escarpment on the flow characteristics is not pronounced at far upstream locations.
- Gentle slopes facilitate smooth flow acceleration with reduced turbulence, whereas steep slopes cause flow separation and recirculation zones, leading to higher turbulence intensity.
- The maximum wind velocity amplification for both the escarpments is observed at the crest. For the gentle slope, a maximum amplification of 35% is observed, whereas, for the steeper slope, this value is close to 44%.
- For steeper slope, the maximum reduction in the wind velocity distribution is seen at 1H u/s. Compared to the undisturbed flow, this reduction is approximately 61%.
- The findings of this paper suggest that an ideal location for a building to come up in a terrain as described in this study would be far upstream and far downstream regions. This is due to the fact that at near upstream locations, due to increased wind velocity, the wind loads are increased to a great extent; and at near downstream locations, there is a pronounced effect of the flow separation which causes high turbulence and high suction on the building in this region. On a contrary note, for Wind Turbines, an optimal site of placement would be near upstream/crest location, mainly due to the increased wind velocity and low

turbulence at these locations. This would ensure that there is maximum harnessing of the wind energy.

- Further studies incorporating varying wind conditions, more complex terrain profiles, and additional structural configurations would be beneficial for broader generalization for the ideal location for a building to come up in a complex terrain.
- The measuring locations in this study were limited to a maximum downstream distance of 10H due to wind tunnel constraints. Future research should explore extended downstream regions and investigate three-dimensional effects to provide a more comprehensive understanding of wind flow over varied escarpments. Furthermore, the effect of upstream surface roughness on the results presented in this paper can also be a subject of future investigation.
- Future work could also incorporate CFD simulations to extend the findings of this study.

List of Abbreviations

IBL	Internal Boundary Layer
UFC	Undisturbed Flow Case
U/S	Upstream
D/S	Downstream

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