Along-Wind Aerodynamic Forces on a Rectangular Plan Building in Vicinity of a Gently Sloped Two-Dimensional Hill

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Abstract

Many engineering applications, such as wind energy distribution for optimum site selection for wind farms, pollutant dispersion, forest fire propagation and wind loads on structures in hilly terrains require a thorough understanding of the wind flow. The assessment of wind loads on buildings and structures located on exposed hill sites is a key application for understanding the effect of topography. This paper presents a wind tunnel investigation of along-wind aerodynamic forces on a rectangular plan building located near and on top of a gently sloped sinusoidal hill. The hill model has a slope equal to 15° and extends fully across the width of the wind tunnel in the direction perpendicular to the wind flow. A force measurement study is carried out on a rectangular plan rigid building model, which is placed near and on top of the hill at a total of 17 successive locations. Results measured include along-wind base shear forces and base moments. It is observed that the along-wind force gradually increases, as the building is moving closer towards the crest. The maximum along-wind base shear force for the building is reported just upstream of the crest. Increased along-wind base moment for the building up to a factor of 4.0 is observed at the crest. This paper is expected to be of great help to structural engineers for designing buildings in hilly terrains.

Keywords: Wind tunnel; Two-Dimensional hill; Rectangular building; Along-wind forces; Along-wind moments

1 Introduction

In order to evaluate the localized wind speed and direction at a location in a hilly terrain, a thorough understanding and knowledge of the atmospheric boundary layer modification caused by sudden changes in the local topography is required (Bowen & Lindley, 1977). The contemporary approach to the analysis of boundary layer flow over hills may be traced back to a series of theoretical studies published in early 1970’s, the most notable of them being that of Jackson & Hunt (1975), where they provided an in-depth analytical answer for airflow over a gently sloped hill . Other fairly good numerical models for wind flow over hills include those of (Deaves, 1975, 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. Other studies on boundary layer flow over hills include the review papers by (Taylor et al., 1987; Finnigan, 1988).

Notable field studies on wind flow over hills include the work of (Mason, 1986; Salmon et al., 1988). Other wind tunnel studies include those of Gong & Ibbetson (1989), Ferreira et al., (1991, 1995); (Kim et al., 1997); (Carpenter & Locke, 1999); (Cao & Tamura, 2006); and (Li et al., 2017). Recent studies on flow over complex/hilly terrain include the work of Hyvärinen et al., (2018), Kozmar et al., (2018), Fang et al., (2019), and Kilpatrick et al., (2021). Most of the studies in the past reported mean wind flow and turbulence characteristics over the hill models of different geometries and slopes. A limited number of studies have been conducted from the perspective of structural loading which include the work of (Bitsuamlak et al., 2007) and (Cheynet et al., 2016). However, when it comes to evaluate wind effects on buildings or structures, which are located in hilly terrains, the literature available is scarce. Most of the structural designers follow the standard codes of practice for wind loads, which either underestimate or overestimate the wind loads for buildings located in vicinity of a topographic feature like a hill or an escarpment. This study is an attempt to evaluate the wind effects on a building located near and on top of a two-dimensional hill placed in a boundary layer wind tunnel.

The main objective of this paper is to evaluate the along-wind forces and base moments of the building model placed successively at a total of 17 locations between the upstream and downstream measuring points over the hill model and to compare them with that of a flat terrain. The work described in this paper should greatly assist in the prognosis of design wind loads, which are mostly calculated using standard codes of practice for wind loads of different countries.

2 Materials and Methods

2.1 Characteristics of Wind Flow

Experiments are carried out in an open-circuit boundary layer wind tunnel, which has cross-sectional dimensions as 2 m × 2 m and length of test section as 15 m. The wind tunnel has a contraction ratio of 9:1 at the entrance of the test section. To generate vortices and create a thick boundary layer, vortex generators and a barrier wall are fixed near the entrance of the test section (Fig. 1). The modelled atmospheric boundary layer is characterised by a power-law exponent of 0.2 for the incoming flow. The boundary layer thickness is approximately 900 mm measured from the wind tunnel floor. The approach flow (reference) mean wind velocity and turbulence intensity profiles are shown in Fig. 2.

2.2 Model Description

A two-dimensional symmetrical hill model is prepared using plywood. The hill model is sinusoidal in shape with H/L value equal to 0.54 (gently sloped/shallow hill) (Fig. 3). The geometrical shape of the hill is given by the equation used by Ferreira et al., (1995).

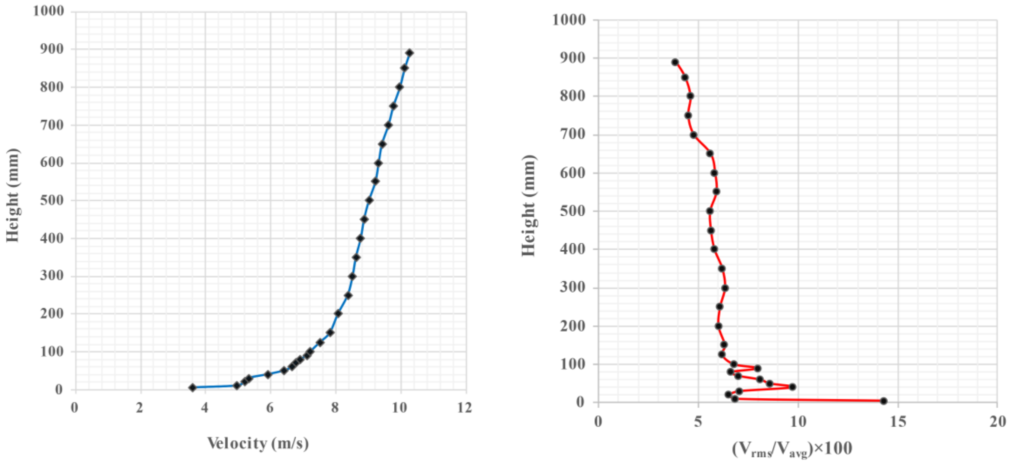
$$z = \frac{H}{2}\left(1 + sin\left(\pi \frac{x-L}{2L}\right)\right) \tag{1}$$

Where H is the hill height, L is the length measured in the direction of wind flow, for z = H/2.

The height of the hill is kept fixed at 300 mm. A geometric length scale of 1:100 is adopted throughout the study.

A force measurement study is carried out in which a rectangular plan shaped building model is made using plywood. The building model is rigid and hence static wind analysis is adequate to evaluate the wind loads. The building has plan dimensions of 200 mm × 100 mm and height equal to 300 mm (Fig. 4).

Fig. 1: Upstream Portion of the Test Section of the Wind Tunnel

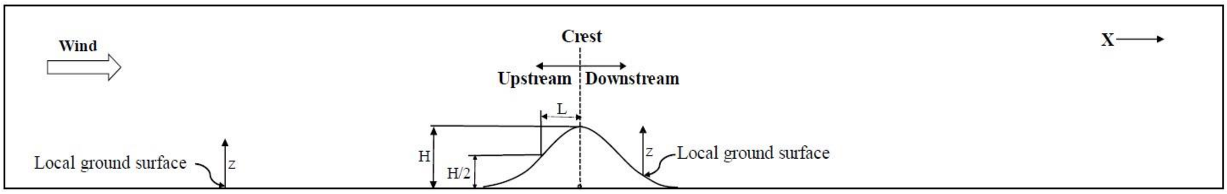


(A) Mean Wind Velocity Profile (B) Turbulence Intensity Profile

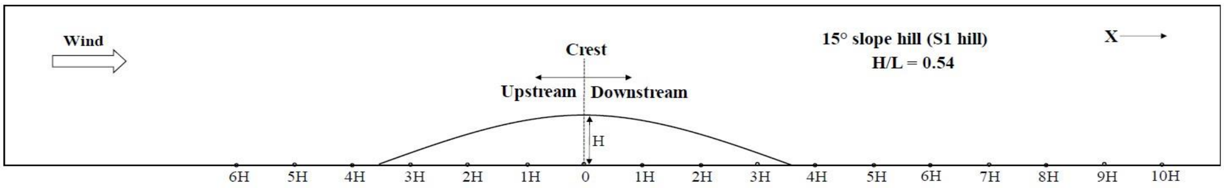
Fig. 2: Wind flow characteristics without the presence of hill (flat terrain)

2.3 Measurement Technique

Mean wind velocity and turbulence intensity for the flat terrain are measured using Testo 480 instrument which has a probe with a 4-blade 16 mm diameter fan fixed on top of it. The Testo 480 instrument is connected to a computer for real time measurement of wind velocity. Force measurement study is carried out by using the 5-component Load cell Nissho LMC-5510-10 (LMC-5510-10 is the model no. and S.no. is 11554) which works at a frequency of 300 Hz. All the experiments are carried out at a mean free-stream wind velocity of 10.3 m/s measured at approximately 900 mm height above the wind tunnel floor. The measurements are made at several locations between 6H upstream and 10H downstream for the hill successively (Fig. 3 (b)). Testo easy climate software (v3.4) was used for real time measurement of wind velocity and dEX-2 data logger software was used for acquiring data from the load cell via, data acquisition system.

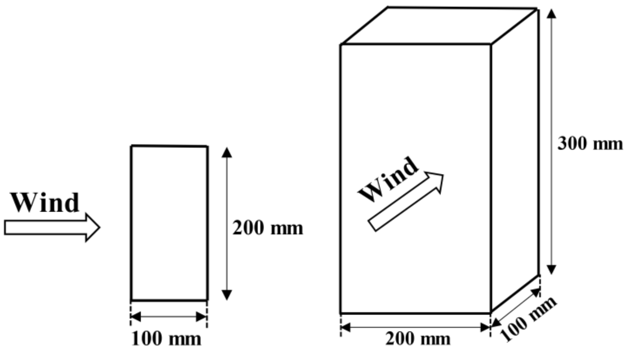


(a)



(b)

Fig. 3: Geometry of the hill models considered for the force measurement study; (a)-general notations of a hill, and (b)-hill model with slope equal to 15°



(a) (b)

Fig. 4: Building model used in the force measurement study; (a)-plan, and (b)-isometric view

3 Experimental Results and Discussions

A force measurement study is carried out on the rectangular plan rigid building model having height equal to 300 mm. The building is placed at successive locations between 6H upstream and 10H downstream in presence of the hill (Fig. 5). The measurements from the five-component load cell include base shear (F_x) and corresponding moment (M_y) in the along-wind direction; base shear (F_y) and corresponding moment (M_x) in the across wind direction and the twisting moment at the base (M_z). The focus will be on results in the along-wind direction. Results are shown for F_x and M_y in Figs. 6 & 7. It is observed that there is increase in F_x as the building continues nearing to the crest and decrease in F_x as the building is placed on the downstream side of the hill. A similar trend is observed for the base moment (M_y). The along-wind force (F_x) is represented in a dimensionless form by a ratio 'F_R' defined as 'along-wind force on the building in presence of the hill at any location between 6H upstream and 10H downstream divided by the along-wind force on the building in an isolated condition (without the presence of hill). As the building location shifts from the farthest upstream location 6H towards the crest, a significant increase in the F_R value is seen. The highest value of F_R reported is 2.00 at 1H upstream. The value at the crest (1.97) is almost equal to the maximum value of 2.00. As the building location shifts from crest towards the downstream side, F_R keeps decreasing, the obvious reason being the flow deceleration occurring beyond the crest till 3H downstream at a rapid rate. The lowest value of F_R reported is 0.91 at 3H downstream, which is just near the downstream foot of the hill. In the region extending from 4H downstream till 10H downstream, the F_R value is seen to be nearly constant and close to 1.00 which indicates that the along-wind force is close to that of the isolated case (flat terrain).

(a) (b) (c)

Fig. 5: Few photographs of the force measurement study done; (a)-building at an upstream location, (b)-building at crest, (c)-building at a downstream location

An insight into the numerical values of F_R is quite useful from a structural engineer's point of view. The increase in the value of F_R confined to the region extending from 3H upstream till 2H downstream affirms the need for consideration of increased wind loads for buildings in general, in these regions. At the time of writing this paper, the authors were aware of no other data to compare the results with.

Figure 7 shows the variation of base moment (M_y) ratio represented by M_R. M_R is defined, as the base moment on the building in presence of the hill at any location between 6H upstream and 10H downstream divided by the base moment on the building in an isolated condition (without the presence of hill). A similar insight into the values of M_R reveals that in the region extending from 3H upstream till 2H downstream, a drastic increase in the value of M_R is seen with the highest value being 3.96, occurring at the crest. This observation reaffirms the need of considering increased wind loads and thereby increased moment values at the design stage of the construction of buildings in hilly terrains having a similar feature described in this study.

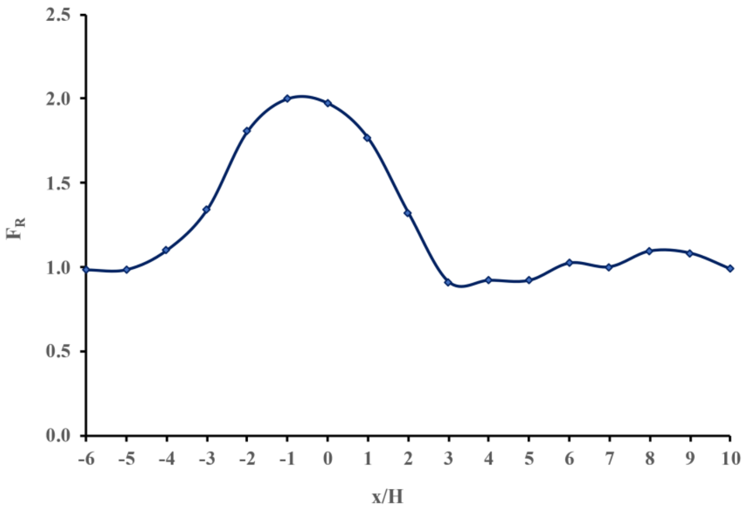


Fig. 6: Along-Wind Force Variation Represented by F_R

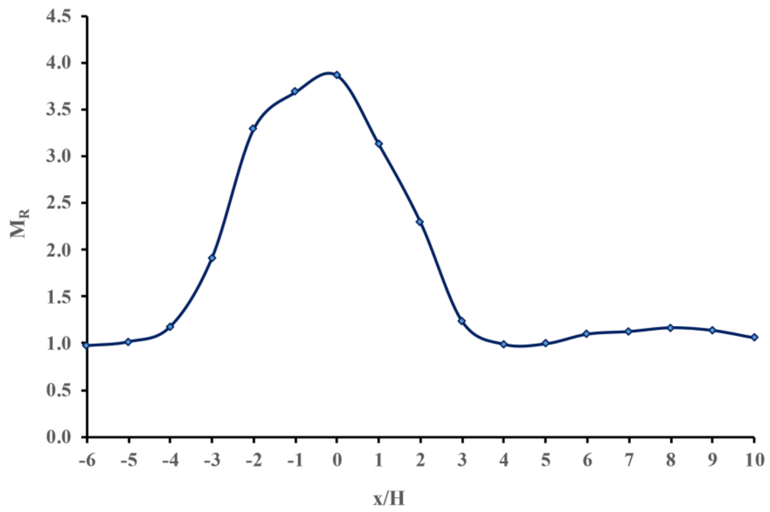


Fig. 7: Base moment variation represented by M_R

4 Conclusions

The present study investigated experimentally the wind effects on a rectangular plan building located near and on top of these hills. Following conclusions can be drawn from the study:

- The approach flow in presence of the hill does not change significantly until it reaches 4H upstream location.
- Due to the gentle slope of the hill, the flow in the upwind slope remains attached and no separation of flow takes place. It is also observed that the along-wind force gradually increases as the building is moving closer towards the crest owing to the significant acceleration of flow as it moves along the slope.
- The maximum along-wind base shear force (F_x) for the building in presence of the hill is observed to be exactly twice (at 1H upstream) the value of along-wind base shear force for the building without the presence of hill (isolated/flat terrain case).
- The highest value of M_R for the building is equal to 3.96 at the crest. This reaffirms the need to take increased base moments up-to a factor of 4.0 for the buildings at the design stage.
- The work presented in this paper should be of great assistance to structural engineers while designing buildings for wind loads in such hilly terrains.
- This paper presents the results for a two-dimensional hill with a gentle slope. Further studies can be carried out for hills with steep slopes.
- Only one row of hill is considered in the present study. Future scope of this work can include making the models of multiple hills and carrying out a similar study. Furthermore, the current study is based on a two-dimensional hill however, a study can be carried out on a three-dimensional hill.

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