Characterization of Mean and Turbulent Flow over Complex Topography under various Inflow and Geometric Configurations

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Abstract

An experimental investigation of flow over a complex topography was undertaken to study the influence of inflow conditions including Reynolds number, upstream roughness, and inflow shear profile on mean and turbulent flow behaviour.

Large-scale physical testing was employed over the escarpment of a hill, spanning a Reynolds number range of $3.6 \times 10^4$ to $5.2 \times 10^5$. Measurements taken using Particle Image Velocimetry (PIV) and Cobra Probes were analyzed in terms of mean and turbulent statistics. Coherent structures were characterized through Proper Orthogonal Decomposition (POD).

The results show that the Reynolds number had little effect on the flow behaviour, while the effect of changing upstream roughness was low to moderate. The modified inflow shear profile had a significant impact, greatly increasing turbulent kinetic energy. A sharper escarpment leading edge had the largest impact by far, significantly altering the flow dynamics. The turbulent flow behavior over the sharper escarpment was found to be similar to the classical case of forward-facing step.

Keywords

Complex topography, escarpment flow, Bolund Hill, forward-facing step, turbulent flow, boundary-layer, wind tunnel modeling, inflow conditions, wind energy, wind resource assessment.
Co-Authorship Statement

Chapter Two has been submitted for publication under the co-authorship of Hangan, H., Siddiqui, K., Parvu, D., Lange, J., Mann, J., and Berg, J. For this chapter, the experiments were carried out by the lead author (Kilpatrick, R.) in conjunction with Lange, J. Parvu, D. assisted with experimental setup and measurements. The lead author completed the data analysis, prepared the draft text, and prepared the final text after seeking review from the co-authors.

Chapter Three will be submitted for publication under the co-authorship of Siddiqui, K. and Hangan, H.
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Chapter 1

1 Introduction

1.1 Background

In the latter part of the 20th century, the wind energy industry experienced tremendous rates of growth. Large turbines with megawatt capacity became commonplace, for both onshore and offshore applications. While not without environmental and social impacts, wind turbines represent a clean, cost-competitive source of renewable energy. As the evidence for the human and environmental risks of climate change continues to mount, wind energy remains an essential part of a combined strategy that can help to reduce the world’s dependence on fossil fuels, allowing for transition to a low carbon economy.

From 2007-2014, global installed wind capacity grew by an average of 22% annually [1], and by the end of 2014, wind power represented 3.1% of global electricity usage [2]. Drivers for this growth have come from a combination of strong policy, which provides incentives to stimulate development, as well as technological advances allowing for larger, more efficient turbines, improved control systems and more accurate predictions of local wind conditions.

For the wind developer, accurate predictions of wind speed at a given location are critical for fulfilling power supply contracts, given that turbine power output is proportional to the cube of the wind speed as shown below [3]:

\[ P_{out} = \frac{1}{2} \rho U^3 (\eta_{mech} C_p) \]  \hspace{1cm} (1.1)

where \( P_{out} \) is the overall turbine power output, \( \rho \) is the density of air, \( U \) is the wind mean velocity, \( A \) is the cross-sectional area, \( \eta \) is the overall turbine efficiency, and \( C_p \) is the rotor power coefficient.

As the wind industry continues to grow, increased attention has been given to the development of wind farms in more complex terrain, taking advantage of the often high wind resources found in these regions. Reliable assessments of the local wind conditions
at these sites, and thus the design of wind farms, have become more challenging due to the changes imposed by the terrain, which may include regions of flow separation, high surface-normal velocity and unsteadiness [4]. A better understanding of these effects and under what conditions they appear, can improve predictive models and ultimately wind farm performance.

1.2 Atmospheric boundary layer

The atmospheric boundary layer (ABL) comprises the region directly above the earth’s surface, varying between a few hundred metres to roughly one kilometre high. At ground level, the no-slip condition causes the wind speed to be reduced to zero. Within the ABL, the viscous or laminar sub-layer is the closest to the surface, and is only a few millimetres thick. Above this resides the Prandtl layer, which comprises about 10% of the ABL. The remaining roughly 90% is occupied by Ekman layer, where the Coriolis force and the pressure gradient force are not in balance [5].

The characteristics of the ABL are influenced by the geomorphology of the surface. Figure 1-1 shows the shape of the ABL over smooth terrain, as well as a simplified example of how it can be modified by the influence of topography, such as a hill. The presence of the hill causes a speed-up region at the hill crest, before wind speeds return to the form of the inflow profile at higher elevation.

![Diagram of Atmospheric Boundary Layer](image)

Figure 1-1: Atmospheric boundary layer over smooth terrain (left) and modified profile over a hill (right). Adapted from Teunissen et al. [6].
The atmosphere can be classified according to vertical stability, i.e. the presence or absence of buoyancy that induces vertical motion of air particles. Stability is linked to weather systems, and can exist in one of three regimes: stable, unstable and neutral. Neutral conditions, where buoyancy is not a factor, often occur in systems with cloudy skies and moderate to high winds. The mixing generated from strong winds, and the reduction of temperature fluctuations at the surface due to cloud cover result in an absence of temperature stratification. Eddies generated by friction can be interpreted as roughly circular and increasing in diameter with height [7].

In stable conditions, vertical movement is dampened, eddies are more compressed, resulting in a steeper wind gradient. On the other hand, for unstable conditions, thermal effects become increasingly important with height, causing vertical stretching of eddies and a flatter wind gradient [7]. Figure 1-2 illustrates the different stability classes.

![Diagram of atmospheric stability](image)

**Figure 1-2: Atmospheric stability. Adapted from Oke [6].**
For neutral atmospheric stability conditions, wind speed can be related to height and surface roughness through the logarithmic wind profile given as [3]:

\[ U_z = \frac{u_*}{\kappa} \ln \frac{z}{z_0} \]  

where \( U_z \) is the mean velocity, \( u_* \) is the friction velocity, \( \kappa \) is the von Karman constant, \( z \) is the height above ground level, and \( z_0 \) is the roughness length.

### 1.3 Wind resource assessment and modeling

Once a candidate wind farm site has been identified, detailed wind resource assessment typically consists of taking measurements of wind conditions at one or more mast locations for a period of 1-3 years, and then extrapolating to predict the entire wind field using a modelling technique involving a set of equations expected to represent actual flow conditions [8]. These micro-scale models, applicable to the lower portion of the ABL, describe atmospheric processes with scales of less than a couple of kilometres. Historically, neutrally stratified flow has been assumed for these models, however non-neutral flows have recently received increased attention.

Micro-scale models for wind resource assessment can be classified into several categories. These models, in order of increasing complexity and required computational power are: linearized models based on the equations formulated by Jackson and Hunt [9], Computations Fluid Dynamics (CFD) such as Reynolds Averaged Navier Stokes (RANS), and Large Eddy Simulation (LES). Use of linearized models remains widespread in industry, although recent years have seen an uptake in the adoption of CFD modelling. LES is at present generally confined to research and academia, however given the advances in computing power, it may soon be adopted by industry [10], [11].

In a relatively flat or gently sloped terrain, linearized models generally produce good results, in line with actual wind characteristics [12]. However, in complex terrain, where abrupt changes in elevation can produce significant changes to wind flow patterns within short distances, linearized models have been shown to produce inaccurate results. This is particularly the case in regions of flow separation, high vertical velocity and unsteadiness
The use of more advanced modelling techniques produces better results for complex topographic terrain, but comes with drawbacks in terms of computational expense, which can be restrictive for commercial development. Gasset et al. [12] estimated the computational cost of CFD estimated to be around one hundred times that of linear models. In addition, CFD modelling generally requires a higher degree of user experience. Results are subject to user input, and significant variation in results can arise depending on the selection of boundary conditions, turbulence closure models and other parameters. This is illustrated for example by the wide variation of CFD results in the Bolund blind comparison where over 50 different numerical and physical models were compared against field data over the steep Bolund Hill escarpment [13], pictured in Figure 1-3.

![Figure 1-3: The Bolund Hill escarpment](image)

Wind farm developers are obviously concerned with generating as much revenue as possible from a given wind farm while minimizing expenses, which naturally entails maximizing turbine output, reducing downtime and maintenance, and avoiding additional payments for missing power production targets agreed to in the supply contract. So one question that arises, is whether there is an advantage for the wind developers to adopting a more sophisticated modelling approach, given the drawback of additional time and resources required, and can this be quantified?

Although many studies identify possible improvements to the accuracy of wind speed estimates for an individual wind turbine or farm, relatively few quantify the potential improvement in Annual Energy Production (AEP) across multiple sites. A study by
Hristov et al. [15] on behalf of wind developer Vestas, analyzed data from 50 sites, and found an overall improvement of roughly 8% when CFD was used for micro-siting, compared to using the linear WAsP model developed by the Technical University of Denmark (DTU). Sites with highly complex terrain saw a 12% improvement when CFD was employed. It is expected that more multi-site studies analyzing the relative advantage of selecting more sophisticated modeling techniques will emerge in the coming years as the database of operating wind farms in complex terrain continues to grow.

So while it is currently difficult to precisely quantify the extent of the problem in terms of an average financial or production penalty, many studies have shown that a more sophisticated modelling approach, and a better understanding of the local wind regime can yield more accurate estimates of wind speed and turbulence characteristics. This creates an opportunity for improved overall wind turbine performance including higher AEP and reduced fatigue loading and associated maintenance costs, and also represents for the wind developers, an overall reduction in the risk associated with a particular project, which has served as strong motivation to sustain ongoing research in this area.

1.3.1 Wind tunnel modeling

While full-scale field measurements are ideal for gathering information on atmospheric phenomena, they are not always practical given accessibility, cost and time restraints. Wind tunnel modeling using scaled topographic models has proven to be an effective tool in analyzing flow behaviour, particularly for complex topography, where non-linearity and unsteadiness are common. Wind tunnel data have also shown to be useful improving the parametrization of sub-models in used in CFD as well as for the validation of new computational models.

In order for wind tunnel flows to accurately represent the full-scale flow behaviour, a number of similarity laws must be fulfilled. These are expressed as non-dimensional parameters and include the Richardson, Eckert, Prandtl, Rossby and Reynolds numbers. All of these similarities are unlikely to be achieved in practice however, and certain simplifications must be made [16]. These simplifications necessarily affect the degree to which the flow over the scaled model is an accurate representation of the full-scale flow,
and determining which parameters can be relaxed is one of the main challenges of wind tunnel modelling. The Richardson and Eckert numbers are related to atmospheric flow stability conditions, and are satisfied under neutral flow conditions. The Prandtl number is the ratio of the viscous diffusion rate to the thermal diffusion rate, and is satisfied in the wind tunnel since air is used as the test medium. The Rossby number measures the degree to which a flow is affected by Coriolis forces compared to inertial and centrifugal forces, and cannot be satisfied in the wind tunnel. Full Reynolds number similarity is also practically impossible to achieve in wind tunnels, however the working assumption is that Reynolds number independence is achieved at some threshold, i.e. Re > 3×10^4 [17], although the degree to which this applies throughout the entire flow, especially in strong vortical regions, remains a subject of investigation.

A wide variety of terrains have been tested in wind tunnels including forest canopy, ridges and valleys, hills and mountains of varying steepness, both isolated and in series. Several studies focused on hills are summarized here as they are more applicable to the current work. Ishihara et al. [18] investigated mean and turbulent flow behaviour of three-dimensional steep hills, focusing on the structure and dynamics of the turbulence in the near-wake region behind the hill. Ferreira et al. [19] examined flow over two-dimensional sinusoidal hills at Reynolds numbers ranging from 1.8×10^4 to 2.5×10^5, and found Reynolds number independence to be achieved only at Re = 9×10^4. Furthermore they found the shape of the hill to strongly influence the extent of the recirculation region, with steeper hills yielding much larger recirculation zones. Cao et al. [20] examined both upstream and surface roughness effects of turbulent boundary layer flow over a steep hill. They found that speed-up over the hill crest was larger for a rough hill, and that the size of the separation bubble was larger for the rough hill, with longer reattachment lengths. Athanassiadou et al. [21] conducted wind tunnel experiments of flow over a series of small hills (10° and 20° slope) with rough surfaces, observing flow separation on the steep hill case but not over smaller ones, as well as good agreement between wind tunnel results and analytical predictions. McAuliffe and Larose [22] conducted high Reynolds number (between 2×10^5 and 8×10^5) experiments of flow over a 1:1500 scale model of the topography of the Gros-Morne wind farm, situated near a coast in complex terrain featuring a number of high hills (up to 600 m). They highlighted the
need for enhanced surface roughness of the model to satisfy Reynolds number scaling, as well as ensuring large turbulence length scales in the upstream flow.

1.4 Motivation and objectives

Separating and reattaching flows, which occur often in steep terrains, are a known challenge for the computational models used in wind resource assessment. The wind industry standard until very recently has been the use of linearized models, which have proven to be successful in flat and gently sloping terrain, but cannot adequately resolve the flows in more complex terrain. To maintain industry growth, efficient power production and thus accurate wind resource estimation in terrains of all types is required, necessitating the use of non-linear analysis [23]. There has been considerable movement toward the use of non-linear models among industry players in recent years, illustrating the practical applications of research in this field. Although CFD has been shown to produce more accurate results over complex terrain than linearized models, there is a wide range of available CFD codes, and depending on the user inputs, a large variation can be produced for the same topography. Thus, a better understanding of the underlying fluid dynamics, particularly around regions with separated and reattaching flows, can provide modelers with better information with which to choose appropriate turbulence closure models and boundary conditions. Better estimates of local wind speeds and turbulence characteristics should allow for better optimization of wind farm design, increasing annual energy production (AEP) and minimizing unnecessary fatigue due to loads induced by turbulence. This will ultimately allow wind farms to be more productive in complex terrain and thus more competitive with other forms of power generation.

There is currently a gap in the scientific knowledge with regards to how the flow behaviour over complex topography is influenced by the geometry of the topographic features, as well as by changes to the inflow conditions. This lack of complete understanding is evidenced by disagreement in predictive models of wind flow. In a review of wind flow over complex terrain with respect to numerical modeling, Bitsuamlak et al. [24] indicates that speed-up over multiple steep hills tends to be over-predicted by various numerical models, and agreement between models and experimental data tends to be worse on the downstream side of a hill than on the upstream areas. Wind
tunnel modeling, when conducted rigorously, can provide useful insights into flow behavior, however this has not always been the case. In a review of wind tunnel experiments of ABL flow over hills conducted in the last 15 years, Petersen [25] describes several limitations, including unclear influence of Reynolds number and establishment of Reynolds number independence, as well as a lack of documentation concerning inflow conditions and experimental setups in general.

Another research area that has received relatively scant attention is related to geometric down-scaling of topographic features, particularly fine features, to produce scaled topographic models for the wind tunnel testing. The extent to which accommodations and adjustments to the scale model need to be made to suitably reproduce the behaviour of flow over these features at full-scale is not well understood. Properly accounting for surface roughness of wind tunnel topographic models has received relatively more attention, but further research is still required to fully understand the impact of changing roughness and other small-scale complex feature, particularly in cases where multiple elements are present, for example rugged terrain with a cliff.

Furthermore, much of the wind tunnel testing over complex terrain has been conducted with a classical boundary layer profile under neutral atmospheric stability and steady flow conditions, and from one wind direction at a time. The impact of wind gusting, for example, over complex topography has not been adequately addressed.

1.4.1 Objectives

Based on the above motivation, the objectives of the present study were:

- To investigate the influence of scaling and inflow conditions on the mean and turbulent flow behaviour over a complex topography
- To investigate the underlying processes associated with this behaviour with respect to the turbulent flow characteristics

An experimental approach has been adapted to meet the research objectives. To fulfill the first objective, the influence of Reynolds number, upstream roughness and changes to the inflow shear profile for flow over The Bolund hill escarpment an escarpment were
examined at two scales. This particular topography was chosen for several reasons: it has become a challenging test case for validation of numerical models for flow over complex terrain, given its very sharp (90°) face on the windward side. Because of this, it has received considerable attention from researchers, and in addition to full-scale field measurements, there are also numerous datasets from physical and computational modelling against which the current work can be compared. Finally, the long upstream fetch over open water of the full-scale cliff is highly suitable for matching the same inflow conditions in the wind tunnel.

The mean speed-up turbulent kinetic energy (TKE) were compared to the full-scale field results, in addition to the results of other physical models to determine any scaling effects. The large-scale WindEEE dome allows for testing under a wide range of inflow conditions as well as at very high Reynolds numbers compared to typical wind tunnels. By conducting a separate set of experiments at the smaller-scale Boundary-Layer Wind Tunnel Laboratory, the present study thus covered a wide range of Reynolds numbers (from $3 \times 10^4$ to $5 \times 10^5$). Another parameter, the inflow surface roughness, was varied by several orders of magnitude and the resulting impacts on the flow were analyzed. Manipulation of individual fans to create customized inflow profiles that differed from the classical boundary layer flow was also employed. Finally, the fidelity of reproduction of fine topographic features in the scaled models, such as the escarpment leading edge, was examined in terms of its influence on the flow behaviour.

The second objective was fulfilled through characterization of the coherent structures and turbulent behaviour of the flow over the escarpment. The applicability of the flow over the escarpment topography to the canonical bluff body flow over a forward-facing step is examined, as is the extent of flow separation and reattachment lengths, highly relevant to design of wind farms in regions of steep terrain.

It is anticipated that this work will contribute to the broader research area by demonstrating the significance of inflow conditions to flow behaviour over topography, which is valuable in both physical and computational modelling environments. In
addition, this work offers a new dataset of turbulent characteristics for separated flows in steep terrain at high Reynolds numbers.

1.5 Organization of the thesis
This thesis is written in the “integrated article” format as specified by the Faculty of Graduate Studies at Western University.

Chapter 1 contains background information on the history of research and challenges faced in characterizing the flow over complex terrain, mainly for the purposes of wind resource assessment and wind turbine siting. Aspects of the fundamental fluid dynamics are presented as they relate to the various sub-topics.

Chapter 2 investigates the mean and turbulent flow behaviour over a scale model of the Bolund hill, and the response of this behaviour to a range of input conditions. Physical modeling is conducted by means of Particle Image Velocimetry (PIV) and Cobra Probe measurements, and the results are compared against field measurements for the full-scale hill. Chapter 2 is based on an article submitted to the journal Wind Energy Science.

In Chapter 3 an in-depth investigation into the turbulent coherent structures in the flow above the hill is performed using the proper orthogonal decomposition (POD) technique. A comparison is also made between the flow topology over the escarpment, and that of the canonical forward facing step, through comparison of turbulent statistical profiles. Chapter 3 forms the basis of a paper to be submitted to a fluid mechanics journal.

Finally, conclusions are presented in Chapter 4, along with suggestions for future work in this area.
References


Chapter 2

2 Mean and Turbulent Flow Behaviour

2.1 Introduction

Wind turbines over the last few decades have emerged as a reliable and cost-competitive means of producing clean, renewable electricity. Although typically built on relatively flat terrain such as plains and farmland, wind farms are increasingly being placed in more rugged, or complex, terrain, marked by abrupt changes in elevation [1].

These sites often have strong wind resources, yet designing wind farms for these regions involves additional challenges due to the changes imposed by the terrain on the three-dimensional structure of the wind, such as speed-up regions, changes to the wind shear profile, large vertical wind velocities, and modification of turbulence characteristics [2], [3].

As a result, the essential prediction of on-site wind conditions, often estimated from measurements at a limited number of mast locations, also becomes more challenging. The use of linearized models, the current industry standard for wind resource assessment and turbine micro-siting, proven to be very effective in gently sloping terrain, can produce inaccurate results when applied at sites with very complex terrain [1], [4]. The use of more advanced modeling techniques such as Reynolds Averaged Navier Stokes (RANS), and Large Eddy Simulation (LES), have generally proven to be more accurate in complex topographic terrain compared to field measurements (e.g. Rasouli and Hangan [5]), and are making inroads with industry, although they come with the trade-off of higher computational cost [6], [7]. These advanced models generally requires a higher degree of user input and experience and thus results can be significantly affected by changes to boundary conditions, turbulence closure models and other parameters, as shown for example in the wide spread of CFD results in the Bolund blind comparison exercise [9].

Thus, a better understanding of the wind regime in complex terrain, from a fundamental fluid dynamics perspective, is critical, given the opportunities for improved overall wind turbine performance including higher annual electricity production and reduced fatigue
loading and associated maintenance costs [4], [9]. This improved understanding of the flow behaviour can be used by modellers to select appropriate boundary conditions and turbulence models with greater confidence. One area that is not fully understood, and forms the subject of this study, is the sensitivity of the mean and turbulent response of the flow over complex topography to changes in the inflow conditions.

2.1.1 Wind tunnel modelling of flow over topography

In order to improve computational models, the model results need to be validated against actual flow conditions. Full-scale testing is ideal for this purpose, however due to the lack of control of inflow conditions, significant testing cost, time and effort required, wind tunnel modelling has served as a valuable tool for development and validation of both numerical and analytical models [10]. Provided that certain conditions are met, measurements taken of the flow across a scale model can provide very useful and repeatable representations of full scale conditions as well as benchmarking for the validation of numerical and analytical models. The controlled environment of the wind tunnel provides a means of isolating the effects of various parameters on the mean and turbulent flow behaviour, which is usually not possible in the field.

There are several examples of wind-tunnel experiments conducted on flow over scale models of real topography for the purpose of wind resource assessment and wind turbine siting. These include isolated hill cases such as Askervein Hill [11], Kettles Hill [12], and more recently Bolund hill [4], as well as highly topographically complex regions with multiple hills and valleys [13], [14], [15].

2.1.2 Bolund experiment

The Bolund experiment arose from the need for additional model validation of flow in a complex terrain, extending the Askervein Hill Project of the early 1980s by offering steeper terrain and thus a greater challenge for numerical models to resolve. Bolund hill is a peninsula located near Roskilde, Denmark, and is characterized by a long upstream open fjord fetch, a steep escarpment and a long flat section on top of the island. The Bolund topography is geometrically similar to a typical wind turbine site in complex terrain, albeit at smaller scale, and is well-suited as a test site given its well-defined,
undisturbed inflow conditions, neutral atmospheric stratification and relative absence of thermal and Coriolis effects [4]. Although Bolund is a small hill, approximately 12 m high by 75 m wide and 130 m long, similarity laws allow for upscaling of 10 – 30 times under neutral atmospheric stratification.

Studies of the wind flow over Bolund hill include the original field campaign [4]; follow-up Lidar measurements of the escarpment wake [16]; computational and physical modelling of the hill as a part of the blind comparison test [8]; wind tunnel modelling [17], [18]; and LES modelling [18][18]. During the field campaign, measurements were taken via 35 anemometers on 10 masts, positioned along two main incoming flow directions referred to as, Line A (239°) and Line B (270°). These were the benchmark measurements against which the results of subsequent modelling efforts have been compared. A detailed diagram of the Bolund topography, with mast positions and flow directions, appears in Berg et al. [4].

2.1.3 Present study: Characterization of mean and turbulent flow over Bolund across a range of input conditions

The present study is focused on the characterization of the flow over Bolund hill, along Line B, in the vicinity of the escarpment, using two physical scale models (1:100 and 1:25), at Reynolds numbers (based on model hill height and wind speed at hill height) ranging from 4×10⁴ to 5×10⁵. The main objectives of this study were to isolate and analyze the dependence of the mean and turbulent flow behaviour over the escarpment on various parameters including Reynolds number, inflow wind shear profile, and upstream roughness. The 1:25 scale experiments were conducted at the Wind Engineering, Energy, and Environment Research Institute (WindEEE), while the 1:100 scale experiments were conducted at the Boundary Layer Wind Tunnel Laboratory (BLWTL). Both facilities are located at Western University. The two sets of results were then compared with the full-scale measurements, and with results from previous studies on Bolund hill. Particle Image Velocimetry (PIV) and Cobra Probes were used for flow velocity measurements at key locations on the scaled models.
2.2 Experimental Setup

2.2.1 WindEEE experimental setup

2.2.1.1 WindEEE facility

The WindEEE dome is a unique wind research facility designed to simulate a wide variety of wind flow patterns including rotational (axisymmetric) and boundary-layer flows at larger laboratory scales. A general description of the facility is provided in [20]. The hexagonal test chamber (25 m diagonal length), is enclosed in a return air chamber of 40 m diagonal length. The WindEEE test chamber contains 106 fans, whose wind speed and direction can be varied independently to produce the desired flow conditions. The facility can be operated in two distinct modes: multi-fan wind tunnel or axisymmetric mode. The present experiment was conducted exclusively under the former configuration, with only the fans along one wall of the hexagon mounted in an array format i.e. four rows of 15 fans each, for a total of 60 fans. Each of these fans are 0.8 m in diameter and operate at approximately 25 m/s at nominal power of 30 kW. Each fan is equipped with variable speed drive and can be individually controlled to create a customized flow pattern. A contraction section was positioned immediately downstream of the 60-fan wall to improve flow uniformity and increase flow speed across the 5 metre diameter test section (turntable) in the centre of the chamber. A trip and a series of spires were employed upstream to enhance turbulence intensity.

In addition to individual fan control, the WindEEE facility also provides the ability to set roughness element position and height, allowing physical simulation of a wide range of incoming Atmospheric Boundary Layer (ABL) flow profiles. There are over 1500 roughness elements in the test chamber, each with maximum height of 30 cm. The present experiment employed only the roughness element sections in the vicinity of the contraction, upstream of the turntable. Two different roughness element configurations, both with uniform element height of roughly 7.5 cm, were used for the WindEEE experiment, hereinafter referred to as RC1 and RC2. For RC1, all of the roughness elements upstream of the turntable were raised, whereas for RC2, one block of about 80
elements immediately upstream of the turntable was lowered to the floor, resulting in a lower effective roughness value than that for RC1.

2.2.1.2 Bolund scale model

The 1:25 scale model of Bolund hill was produced by CNC milling of several large blocks of Expanded Polystyrene (EPS) according to topographical data of the island. These blocks were then glued together and painted black with latex paint. The overall size of the model was roughly 4.5 m across, 0.5 m high, and 3.5 m long. A photograph of the experimental setup is presented in Figure 2-1a.

![Figure 2-1a: Experimental setup for a) WindEEE b) BLWTL.](image)

Figure 2-1: Experimental setup for a) WindEEE b) BLWTL.
A solid ramp with slope of roughly 45° was constructed from EPS and fastened to the
downstream edge of the model to provide a smooth transition and reduce unwanted flow
separation. The model was positioned in the chamber such that the escarpment edge was
roughly 12.4 m from the 60-fan wall, and the plane of measurement (Line B) was parallel
to the flow direction. The $X = 0$ position in the streamwise direction is indicated by the
centre-point of the model, $C_p$, also the intersection of Line A and Line B, as per the full-
scale co-ordinate system, shown in Figure 2-1a. The blockage ratio, defined here as the
ratio of the frontal area of the model at its widest point to the cross-sectional area of the
dome’s test section (5 m × 4 m), was roughly 7.8%.

2.2.1.3 PIV measurement

Particle Image Velocimetry (PIV) was used to measure the two-dimensional velocity
field in a vertical plane above the model, along line B, in the vicinity of the escarpment.
The measurement region encompassed a rectangular area extending roughly from $Z =
11.4$ m to 25 m and $X = -70$ m to $X = -20$ m in the full-scale Bolund co-ordinates, where
the value $Z = 0$ corresponds to sea level. Three 12 megapixel cameras (IO Industries Flare
12M125-CL), each with 105 mm f/2D Nikon AF DC-NIKKOR lenses, were used to
capture images. The cameras were positioned in a row parallel to the flow direction,
facing the model at a distance of roughly 3.55 metres from the camera lens to the
measurement plane, at a height such that the bottom of the camera frame of view was just
below the hill surface. Camera resolution was 4096 × 3072 pixels, and the corresponding
measurement field of view for each camera in the current setup was about 0.78 m wide
by 0.58 m high. The horizontal positions of the cameras were set in a way to form
overlap among the adjacent fields of view to ensure spatial continuity of flow
measurements. The overlap between cameras 1 and 2 was 0.167 m, and between cameras
2 and 3 was 0.088 m, with camera 1 being the most upstream. Thus the combined
measurement area was roughly 2.09 m wide by 0.58 m high.

A Litron Nano Piv Series dual cavity Nd:YAG laser with the energy of 425 mJ/pulse
operating at the wavelength of 532 nm was used to illuminate the flow field. The laser
was positioned directly behind the model, pointing upstream, coincident with Line B,
with the laser head roughly 0.60 m off the ground, as shown in Figure 2-1a. A 50°
cylindrical lens was positioned immediately in front of the laser head to convert the beam into a two-dimensional sheet. The laser was synchronized to the cameras and the frame grabber. In this study, the pulse repetition rate for each laser cavity was set at 9 Hz resulting in the image acquisition rate of 18 frames per second by each camera or 9 Hz for each image pair. The images were acquired via Coreview software (IO Industries) as 8-bit grayscale images in the TIFF format. PIV data were recorded for 5 minutes per test case, providing roughly 2700 image pairs. An Ultratec CLF-4460 commercial fog generator, positioned in the dome’s upper plenum, was used to seed the test chamber with non-toxic, water-based smoke that served as the tracer.

2.2.1.4 Cobra Probe measurement

Cobra Probes, manufactured by Turbulent Flow Instrumentation Pty Ltd., are dynamic multi-hole pressure probes for measuring all three components of mean and fluctuating velocities and static pressure. In the present experiment, Cobra Probe measurements were taken at an upstream reference location, as well as a few positions along the hill. A vertical array of eight Cobra Probes was used, with spacing between probes ranging from roughly 5 cm near the bottom of the array to 15 cm near the top. The total vertical measurement distance was about 60 cm, or 15 m in full-scale. The upstream reference position was located 4.44 m upstream of \( C_p \) in the model scale, or \( X = -111 \) m in the full-scale. Although initially intended for the Cobra probe position to coincide with the full-scale upstream reference mast M0, located at \( X = -180.8 \) m, this was not possible in the current setup due to the proximity of the model to the contraction opening. However, the current location was deemed to be sufficient as a reference location given that it was far enough from the fan wall to assume fully mixed flow and far enough from the model to avoid significant slow-down effects. Along the hill, Cobra Probe measurements were taken at the escarpment edge (\( X = -54.7 \) m), at M6 (\( X = -46.1 \) m) and at M3 (\( X = 3.2 \) m), where values in parenthesis are full-scale co-ordinates. Due to time constraints, Cobra Probe measurements at these positions were not taken for each of the PIV test case configurations. The probe array was mounted either on a stationary floor rack, or fixed to the overhead rail system, and moved to various positions along line B. All Cobra Probe
measurements were conducted at acquisition rate of 10,000 Hz, output to file rate of 1250 Hz, and sampling time of 120 seconds.

2.2.2 BLWTL experimental setup

The model used for the BLWTL experiments was a 1:100 scale model of Bolund hill, using the same topographical data as the WindEEE model. The BLWTL model was similarly cut from EPS, in two sections, and fastened together. The model was then fixed to the turntable at the centre of the test section and rotated such that the principal flow direction coincided with Line B (270° wind direction). Figure 2-1b shows a photograph of the experimental setup with wind direction and mast positions indicated. BLWTL Tunnel 1 is an open circuit type with a length of 33 m and has the cross-section of 2.4 m (width) × 2.15 m (height) at the test section. In the present setup, three triangular spires, as well as a bar trip were positioned at the far upstream end of the tunnel, however no active roughness elements were used, in order to simulate upstream conditions with ABL profile over a smooth surface. The blockage ratio, as defined previously, was roughly 2.6%.

Measurements were conducted at a wind speed of 4.6 m/s that corresponds to a Reynolds number of approximately 3.6×10^4, based on the maximum height of the hill (0.117 m in model-scale) as the characteristic length scale. Cobra Probe measurements were conducted along vertical profiles at model-scale positions equivalent to the full-scale coordinates of M0, M7, M6, M3 and M8, as well as at the escarpment (X = -54.7 m in full-scale). The vertical velocity profile was obtained by using two Cobra Probes mounted to the wind tunnel traverse system and the vertical position was incremented after each sample, by 12.7 mm in model-scale, or 1.27 m in full-scale, near the floor, and 50-100 mm (5-10 m full-scale) higher up. The vertical extent of the measurements was about 1.2 m from the floor (equivalent to 120 m in full-scale). PIV measurements were conducted as well, but are not presented here due to a number of issues with data quality.
2.3 Data processing

2.3.1 PIV data processing

PIV instantaneous velocity fields were obtained by cross-correlating the interrogation regions in the first image of the image pair with the corresponding search regions in the second image. An in-house algorithm implemented in image processing software Heurisko® developed by AEON Verlag & Studio GmbH & Co. KG was used for the PIV data processing. The search window and interrogation window sizes were set as 128 and 64 pixels, respectively, while grid size was 16 pixels. Spurious vectors were identified and corrected using a local median test developed by Siddiqui et al. [21]. In this test, the magnitude of each velocity vector is compared with the median of its eight neighbouring vectors. If the vector is outside a certain limit, it is then replaced by the median vector.

Various sources contribute to the uncertainty associated with the velocity vectors obtained from the PIV technique, including particle diameter, seeding density, out of plane motion, velocity gradients, dynamic range, peak locking and Adaptive Gaussian Window (AGW) interpolation [22]. Results obtained from Cowen and Monismith [22], Ayotte and Hughes [10] and Prasad et al. [23] were used to develop the uncertainty estimation. The highest Reynolds number case, in the near-wall region was considered where the mean gradients are highest, since it yields the highest uncertainty, which was estimated to be ±1.7%. Velocity measurements in regions away from the hill surface, where the mean gradients are lower, are expected to have lower uncertainty. The detailed uncertainty analysis is presented in Appendix A.

Mean fields were calculated by averaging the respective velocity component (streamwise, u, and vertical, w, in the present case) at each grid point over the sampling time. The turbulent velocity fields were computed by subtracting the mean velocity from the instantaneous velocity at each grid point in a given velocity field. These two steps were performed using an in-house code in MATLAB.

Mean flow speed, S, was calculated using the two mean wind components U and W from the PIV measurement plane (see Figure 2-1a) as:
\[ S = (U^2 + W^2)^{1/2} \]  

Results shown throughout this work are often expressed as a normalized speed-up ratio \( S(x,z)/S_0(z) \), where \( S_0(z) \) is the upstream reference speed at the same height. Since the upstream reference measurements were taken with Cobra Probes at a limited number of heights, extrapolation to all of PIV grid heights was performed using the logarithmic law (Manwell [24]).

\[ \frac{U(z)}{U(z_r)} = \frac{\ln \left( \frac{z}{z_0} \right)}{\ln \left( \frac{z_r}{z_0} \right)} \]  

where \( z_r \) is the reference height. Mean turbulent kinetic energy (TKE), \( \bar{k} \) was calculated according to:

\[ \bar{k} = \frac{(u'^2 + w'^2)}{2} \]  

where lowercase \( u' \) and \( w' \) represent the fluctuating velocity vectors. The change in TKE, or TKE increment \( \Delta \bar{k} \) was obtained by subtracting the upstream reference TKE \( \bar{k}_{05} \) at a fixed height of \( z = 5 \) m in full-scale (0.2 m in model-scale) from the measured TKE at each PIV grid position and normalizing by the square of the upstream reference speed:

\[ \Delta \bar{k} = \frac{\left[ k(x,z) - \bar{k}_{05} \right]}{S_0^2(z)} \]  

Both speed-up ratio and TKE increment were calculated using only the two velocity components available from the PIV measurements, \( U \) and \( W \), with no attempt made to estimate the magnitude of the span-wise component, \( V \). This was done mainly to enable comparison with previous work, i.e. Yeow et al. [17].

Despite efforts to properly align the three cameras, some minor discrepancies were observed in the velocity data recorded by each camera. For mean wind speeds, error between camera frames typically ranged from about 2-4\%, with slightly more error in the highly turbulent region close to the escarpment and just above the model surface. To improve the clarity of presentation, a frame stitching algorithm using was implemented to smooth the data within the overlap region between camera frames. At each point in the overlapping region, a weighted average of the data at the two overlapping nodes was
taken, such that data points closer to one camera or another were weighted more heavily towards that camera’s values. The weightings varied linearly from 0.5 for each camera at the centre of the overlap region (equal weighting), to 1 and 0 on one side, and 0 and 1 on the other.

2.3.2 Cobra Probe data processing

Cobra Probe output data is generated by the companion TFI Device Control software, and consists of a time history of \( u, v \) and \( w \) wind speed components, as well as a summary output of the mean wind speeds, Reynolds stresses and pressures. Generally only the mean data from the summary files were used, with spot checks performed against the time history data to ensure consistency. The Cobra Probe results presented in this work generally use two-component calculations, where the span-wise wind speed component \( v \) is neglected, as per Eq. 1 and Eq. 3, which allows for direct comparison with the PIV results, which is analogous to the approach adopted by Yeow et al. [17] for hot-wire measurements. However, when comparing the WindEEE and BLWTL inflow profiles, measured with Cobra Probes, against the full-scale data from upstream mast M0, all three wind velocity components from the Cobra Probe data were used.

2.4 Inflow profiles

2.4.1 WindEEE inflow profiles

2.4.1.1 Fan configuration

For the present set of experiments, the 60 fans were operated using four different configurations, which were selected in attempt to match the full-scale incoming wind profile, as well as to produce a range of Reynolds numbers (see Table 2-1):

- All fans running at 20% of the maximum fan RPM
- All fans running at 30% of the maximum fan RPM
- All fans running at 50% of the maximum fan RPM
- Fans in row 1, 2, and 4 running at 50%, fans in row 3 at 75%, of the maximum fan RPM. For reference, fan row 1 is at floor level
The notation for each test case was set based on the upstream wind speed and the upstream surface roughness. That is, each of the four fan configurations are identified by the mean streamwise incoming wind speed at the model escarpment height in m/s (i.e. U5, U8, U14, U15) and the two upstream roughness configurations as RC1 and RC2, where, RC1 corresponds to the higher upstream roughness. For example, case U5RC1 correspond to the test case conducted at the inflow condition of 5 m/s wind flowing over higher roughness. These combinations yielded eight unique flow configurations representing the WindEEE PIV test cases described throughout this work, as listed in Table 2-1.

2.4.1.2 Calculation of Reynolds number, friction velocity and surface roughness

The inflow parameters for the WindEEE experiment in Table 2-1 were determined from the upstream reference Cobra Probe data. Reynolds number was calculated according to:

\[ Re = \frac{U_h h}{v} \]  

(2.5)

where the characteristic length h is the hill height, \( U_h \) is the mean inflow streamwise velocity at h, and \( v \) is the kinematic viscosity of air at 20°C i.e. 1.50\times10^{-5} \text{ m/s}^2. \) The Reynolds numbers in Table 2-1 use the model hill height \( h = 0.468 \text{ m}. \) For the test cases with the same fan configuration but different roughness configuration, Reynolds number was almost identical. For the present study, which focuses mainly on how upstream conditions affect flow behaviour over the escarpment, the means by which the upstream parameters are calculated are important, as there is often some variability depending on the method of calculation. For example, friction velocity \( u_* \) can be determined using several different methods, which often show considerable differences between them [25].

To compare the variability of the resulting normalized upstream profiles for the WindEEE experiment, the friction velocity was calculated using four different methods. For method 1, friction velocity was calculated according to Eq. 6, as per Weber [25] using only the longitudinal component of the Reynolds stress vector, which is the same
method used by Berg et al. [4] to calculate friction velocity using data from the upstream reference mast M0 in the Bolund field campaign.

\[ u_* = (-u'\bar{w})^{1/2} \]  \hspace{1cm} (2.6)

Method 2 adds the span-wise Reynolds stress component and always produces a higher value of \( u_* \) than Method 1 [25], [26]. It is similar to the method used in Bechmann et al. [8] and is given by:

\[ u_* = \left[ (u'w')^2 + (v'w')^2 \right]^{1/4} \]  \hspace{1cm} (2.7)

For Methods 1 and 2, a single reference value \( u_{*05} \) was taken as the friction velocity at a reference height of \( z = 5 \) m in full-scale (0.2 m in model-scale), consistent with the approach used by Bechmann et al. [8] and Yeow et al. [17]. For method 3, upstream effective roughness \( z_0 \) and friction velocity \( u_* \) were determined by fitting the streamwise velocity profile data within the logarithmic region to the standard logarithmic wind profile for neutral stability conditions [24]:

\[ U(z) = \frac{u_*}{\kappa} \ln\left( \frac{z}{z_0} \right) \]  \hspace{1cm} (2.8)

where \( z \) is the vertical height from the ground, \( U(z) \) is the streamwise wind speed at that height, and the von Karman constant \( \kappa \) was considered to be 0.41. Method 4 may be considered a combination of Methods 1 and 3, and follows the approach of Akomah et al. [27], who describe a region of constant shear stress corresponding to the equilibrium sub-layer where TKE production and dissipation balance. The values of friction velocity computed using each of the four methods are presented in Table 2-1. The difference between the highest and lowest estimate was relatively high, ranging from about 15% to 50% depending on the test case. Friction velocity is still calculated using Eq. 6, however unlike in Method 1 where a single data point was used, Method 3 uses the mean of the values within the constant shear stress region, which were identified from the plots of height vs. \( |u'\bar{w}'| \) (as the first three data points closest to the floor for each test run.)
Table 2-1: Inflow parameters for WindEEE PIV test cases

<table>
<thead>
<tr>
<th>Case ID</th>
<th>Fan configuration</th>
<th>$u_0$ (m/s)</th>
<th>Re</th>
<th>$z_0$ (m)</th>
<th>$u_{NG}$ (m/s) Method 1</th>
<th>$u_{NG}$ (m/s) Method 2</th>
<th>$u_1$ (m/s) Method 3</th>
<th>$u_1$ (m/s) Method 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>USRC1</td>
<td>All fans 20%</td>
<td>5.42</td>
<td>$1.70 \times 10^5$</td>
<td>1.84 $\times 10^{-3}$</td>
<td>0.314</td>
<td>0.326</td>
<td>0.254</td>
<td>0.333</td>
</tr>
<tr>
<td>USRC2</td>
<td>All fans 20%</td>
<td>5.49</td>
<td>$1.72 \times 10^5$</td>
<td>1.96 $\times 10^{-6}$</td>
<td>0.229</td>
<td>0.252</td>
<td>0.145</td>
<td>0.231</td>
</tr>
<tr>
<td>U8RC1</td>
<td>All fans 30%</td>
<td>8.70</td>
<td>$2.72 \times 10^6$</td>
<td>1.98 $\times 10^{-3}$</td>
<td>0.488</td>
<td>0.489</td>
<td>0.409</td>
<td>0.505</td>
</tr>
<tr>
<td>U8RC2</td>
<td>All fans 30%</td>
<td>8.57</td>
<td>$2.68 \times 10^6$</td>
<td>4.12 $\times 10^{-7}$</td>
<td>0.373</td>
<td>0.415</td>
<td>0.203</td>
<td>0.355</td>
</tr>
<tr>
<td>U14RC1</td>
<td>All fans 50%</td>
<td>14.60</td>
<td>$4.57 \times 10^6$</td>
<td>2.72 $\times 10^{-3}$</td>
<td>0.856</td>
<td>0.869</td>
<td>0.723</td>
<td>0.848</td>
</tr>
<tr>
<td>U14RC2</td>
<td>All fans 50%</td>
<td>14.69</td>
<td>$4.60 \times 10^6$</td>
<td>2.29 $\times 10^{-6}$</td>
<td>0.668</td>
<td>0.361</td>
<td>0.392</td>
<td>0.640</td>
</tr>
<tr>
<td>U15RC1</td>
<td>Fan rows 1,2,4; 50% Fan row 3: 75%</td>
<td>15.60</td>
<td>$5.21 \times 10^6$</td>
<td>2.87 $\times 10^{-4}$</td>
<td>0.992</td>
<td>1.070</td>
<td>0.650</td>
<td>0.970</td>
</tr>
<tr>
<td>U15RC2</td>
<td>Fan rows 1,2,4; 50% Fan row 3: 75%</td>
<td>15.60</td>
<td>$5.21 \times 10^6$</td>
<td>Not measured*</td>
<td>0.992</td>
<td>1.070</td>
<td>0.650</td>
<td>0.970</td>
</tr>
</tbody>
</table>

Roughness lengths shown in full-scale.

The $z_0$ values were obtained using Method 3, and are presented in full-scale units in Table 2-1. The values show a clear distinction between the RC1 cases ($z_0 \sim 10^{-3}$ m) and RC2 cases ($z_0 \sim 10^{-6}$ m). The full-scale roughness measured at mast M0 was $z_0 = 3 \times 10^{-4}$ (Berg et al. [4] 2011), so the U15RC1 case shows the closest match.

2.4.1.3 Comparison between inflow profiles

Cobra Probe measurements of upstream reference mean flow speed $S_0$ and TKE $\overline{k_0}$, normalized by the $u_*$ values estimated using method 1, are shown in Figure 2-2a, along with the full-scale measurements at M0 (Berg et al. 2011 [4]). A clear separation is observed between the profiles with higher roughness (RC1) and those with lower roughness (RC2), with the RC2 group having higher normalized mean wind speed as well as TKE. Comparison of the upstream mean speeds for the test cases with the full-scale data shows that all model-scale values are lower than the full-scale wind speeds, with the exception of U5RC2, whereas the normalized TKE profiles are all higher than the full-scale profiles, illustrating the inherent difficulty in matching both the mean wind speed and TKE profiles with the full-scale values. The shape of the TKE profiles is in contrast to the wind-tunnel experiment conducted by Yeow et al. [17] whose normalized TKE inflow profiles were lower than the full-scale values, and decreased with height.
Figure 2-2: a) WindEEE upstream profiles of upstream reference mean flow speed and TKE normalized by friction velocity obtained using Method 1, and b) BLWTL upstream profiles of upstream reference mean flow speed and TKE, normalized by friction velocity obtained using four different methods. $S$ and $\overline{k}$ calculated using all three components of wind speed from Cobra Probe measurements. $Z$ co-ordinates shown in full-scale.
Most of the WindEEE normalized TKE profiles are relatively vertical between \( z = 5 \) m and \( z = 12 \) m which is consistent with the full-scale data, although having only two full-scale data points available from the reference mast M0 in the field campaign, none of which were above a height of 12 m (i.e. just above escarpment height), is a limiting factor in determining whether a good match to the full-scale conditions has been achieved.

The results for Method 2 (not shown) are similar to Method 1, with all profiles shifted slightly to the left, given the slightly higher values of \( u_\ast \). There is also less separation between the RC1 and RC2 groups. Inflow profiles determined using Method 3 are somewhat different, with the RC1 profiles showing a better match to the full-scale data for mean speed, although still higher for TKE, but significantly higher values for the RC2 group, for both mean speed and TKE, due to the higher values of \( u_\ast \). Profiles using Method 4 are quite similar to those of Method 1, with profiles collapsing slightly more within the RC1 and RC2 groups.

### 2.4.2 BLWTL inflow profiles

Table 2-2 shows the main test parameters for the BLWTL Cobra Probe measurements. Friction velocity was calculated as per the four methods outlined above, and \( z_0 \) was estimated using Method 3. Figure 2-2b shows inflow profiles from the BLWTL Cobra Probe data, measured at the upstream reference location of \( X = 1.82 \) m in model scale (\( X = -182 \) m in full-scale). Mean speed and TKE were normalized by friction velocity calculated using the four methods identified above. The results show that the profiles for Methods 1-3 are quite close to each other, and higher than the full-scale data points, while Method 4, with higher \( u_\ast \), produced profiles shifted slightly to the left, and matched particularly well with the full-scale data. The reduction in normalized TKE with height was consistent with the inflow profiles measured by Yeow et al. [17], but different from the WindEEE and full scale TKE profiles, which were relatively constant with height over the measurement region.
Table 2-2: Inflow parameters for BLWTL experiment

<table>
<thead>
<tr>
<th>Case ID</th>
<th>$u_h$ (m/s)</th>
<th>$Re$</th>
<th>$z_0$ (m)</th>
<th>$u_{ref}$ (m/s) Method 1</th>
<th>$u_{ref}$ (m/s) Method 2</th>
<th>$u_*$ (m/s) Method 3</th>
<th>$u_*$ (m/s) Method 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>BLWTL</td>
<td>4.65</td>
<td>$3.63 \times 10^4$</td>
<td>$1.266 \times 10^{-4}$</td>
<td>0.1643</td>
<td>0.1651</td>
<td>0.1640</td>
<td>0.1858</td>
</tr>
</tbody>
</table>

2.5 Results and Discussion

The results are divided into two main sections: analysis of the mean flow behaviour, and analysis of the turbulent flow behaviour. Most of the results presented were obtained from the WindEEE PIV data, while some additional data is presented from the WindEEE Cobra Probe profiles, as well as the BLWTL Cobra Probe measurements as necessary.

2.5.1 Mean flow behaviour

The streamlines of the mean flow field are shown in Figure 2-3 for upstream velocities of U5, U8, U14 and U15 at higher roughness configuration (RC1). Mean streamlines for the RC2 cases (not shown) were nearly identical.

![Figure 2-3: Mean streamline plots for test cases with roughness configuration RC1.](image)

The streamline plots do not show a mean recirculation, however, a closer inspection of the mean flow field in the immediate vicinity of the escarpment (see Figure 2-4) shows a possible region of reverse flow within the separation bubble, although the higher uncertainty in the near-wall region prohibits drawing a firm conclusion. Most cases
showed a small stagnation zone just upstream of the escarpment, although it was not observed in the U15RC1 case (Figure 2-4b).

**Figure 2-4:** Mean contours of streamwise wind speed normalized by upstream reference wind speed at hill height, with mean vector field overlaid, for a) U14RC1, and b) U15RC1.

Contour plots of speed-up ratio for U14RC1 (Figure 2-5a) and U15RC1 (Figure 2-5b) clearly illustrate the speed-up region near the escarpment, and the re-establishment of the boundary layer on top of the hill. The U5 and U8 contour plots (not shown) were very similar to the U14 case, analogous to the similarity observed in the streamline plots between the three cases. While speed-up is generally similar between the U14RC1 and
U15RC1 cases, slightly higher values are observed for U15RC1 in the vicinity of the escarpment, and this case also shows a more elongated, oblong shape of the speed-up region at the escarpment edge.

Figure 2-5: Speed-up ratio contour plot for a) U14RC1 and b) U15RC1.

Reynolds number for the two flows did not differ by a great amount (4.57×10^5 for U14RC1 vs. 5.21×10^5 for U15RC1), i.e. much less than the difference in Reynolds number between the U5RC1 and U14RC1 cases, indicating that the difference in
normalized mean flow behaviour can be most likely attributed to the higher upstream shear for the U15 case.

2.5.2 Mean flow comparison to previous experiments

In addition to the full-scale measurements, results from previous physical modelling of the Bolund hill, are available in the literature for comparison to the present results. These include wind tunnel and water channel experiments from the blind comparison of Bechmann et al. 2011 [8], wind tunnel PIV and 3-component hotwire (3CHW) tests conducted by Yeow et al. [17] at 1:115 scale at two Reynolds numbers (4.15×10^4 and 8.21×10^4), and wind-tunnel PIV modeling conducted by Conan et al. (2015) at 1:500 scale and Re = 2.1×10^4. Benchmarking the WindEEE Cobra Probe and PIV, and BLWTL Cobra Probe results from the present experiment against these datasets provides some validation of the present experimental procedure, and also serves as an initial point of discussion on the differences between conducting the same experiment at three scales, i.e. wind tunnel (Re ~10^4), WindEEE (Re ~10^5) and full-scale (4.25×10^6 < Re < 1.02×10^7).

Figure 2-6 shows horizontal profiles of the wind speed-up at two locations corresponding to the full-scale mast measurement positions at heights of z = 2 m (Figure 2-6a) and z = 5 m (Figure 2-6b) above hill surface level. Results from the WindEEE PIV data and those of previous experiments mentioned above are presented for comparison. The topography and the mast locations are shown in Figure 2-6c for reference.

Figure 2-7 shows the comparison for vertical profiles at three horizontal locations along the hill. The U14RC1 and U15RC1 cases were selected from the eight WindEEE PIV cases as representative cases to avoid clutter; the differences between all of the WindEEE cases are discussed further below. From the horizontal profiles, agreement is generally quite good between all datasets at z = 5 m, whereas significant variability is observed at z = 2 m, which is within the highly turbulent shear layer observed in the TKE contour plots (see Figure 2-11), referred to also by Yeow et al. [17] and observed in the scanning Lidar data (Lange et al. [16]). Similarly for the vertical profiles, better agreement is observed at position M7 upstream of the escarpment (Figure 2-7a), with greater variability seen at the other two positions (Figure 2-7b, c), with higher variability at z < 5 m.
Figure 2-6: WindEEE and BLWTL speed-up ratio along horizontal profiles at a) $z = 5$ m and b) $z = 2$ m above surface level for PIV and Cobra Probe measurements with comparison to full-scale and to previous physical experiments.
Figure 2-7: Comparison of WindEEE and BLWTL speed-up ratio along vertical profiles at a) M7 \((X = -66.9 \text{ m})\), b) escarpment \((X = -54.7 \text{ m})\) and c) M6 \((X = -46.1 \text{ m})\) with comparison to full-scale and to previous physical experiments.

2.5.3 Influence of Reynolds number, upstream roughness, inflow profile and model resolution on mean flow

The WindEEE experiments were conducted by changing one variable at a time, allowing for the influence of a particular modifier to the flow to be isolated and the resultant flow behaviour analyzed. In this section, the isolated effects of Reynolds number, upstream roughness, shape of the inflow profile, and scale model and measurement resolution, on the mean flow behaviour are discussed.
2.5.3.1 Reynolds number and upstream wind profile effects on the mean flow

The horizontal profiles of the wind speed-up for four Reynolds numbers at full-scale heights of $z = 5\text{ m}$ and $z = 2\text{ m}$ above the island surface level are shown for two upstream roughness cases; higher roughness RC1 in Figure 2-8a and lower roughness RC2, in Figure 2-8b. Full-scale data are also plotted for reference.

Figure 2-8: Horizontal profiles of speed-up ratio for a) RC1 cases, $z = 5\text{ m}$, b) RC1 cases, $z = 2\text{ m}$, c) RC2 cases, $z = 5\text{ m}$ and d) RC2 cases, $z = 2\text{ m}$.
Although not shown in the plots due to the limits of the PIV measurement window, speed-up is expected to drop off rapidly in the region immediately upstream of the escarpment ($X = -54.7$ m) to as little as $S/S_0 = 0.5$, as seen in the PIV results of Yeow et al. [17], shown in Figure 2-8. Similar behavior was observed in the BLWTL PIV measurements (not shown). The results show almost identical trends of the normalized mean flow for three uniform fan speed cases (U5, U8 and U14), for both RC1 and RC2. This indicates an absence of Reynolds number effect on the mean flow over a Reynolds number range of $1.7 \times 10^5$ to $4.6 \times 10^5$. The U15 case, however, with modified inflow shear profile, displays different behaviour than the uniform fan speed cases. The U15RC1 peak speed-up is higher at the escarpment compared to the other RC1 cases, then changes to become relatively lower further downstream. For the U15RC2 case, speed-up is generally equal or slightly lower than the other RC2 cases at $z = 5$ m (Figure 2-8c), and lower along horizontal locations at $z = 2$ m (Figure 2-8d).

In Figure 2-9, a similar comparison is made along the vertical profiles at M6. Results show a trend similar to that observed for the horizontal profiles, i.e. little difference among the mean flow profiles at three uniform fan speed cases, with the RC2 profiles collapsing more closely.

**Figure 2-9:** Vertical profiles of speed-up ratio at M6 for a) RC1 cases (left) and RC2 cases (right).
Again the U15RC1 case (Figure 2-9a) shows different behaviour, with higher speed-up than the other cases, and also shows a better match to the full-scale data points. For RC2 (Figure 2-9b), the U15 case generally collapses with the others, with the only difference being the relatively lower speed-up for $z < 4$ m which is again closer to the full scale behaviour.

2.5.3.2 Upstream roughness effects on the mean flow

The comparison of speed-up profiles at the same Reynolds number but different roughness configuration provides an insight into the effect of upstream surface roughness, $z_0$, on the mean flow behaviour over the escarpment. Such analysis can be obtained by comparing the profiles in Figure 2-8 and Figure 2-9 for two roughness cases. It is observed that in general, the speed-up profiles for the same Reynolds number at the two different roughness heights were similar, despite relatively significant difference between $z_0$ values, which was about three orders of magnitude larger for RCI compared to RC2. The difference in peak speed-up for two roughness configurations at $z = 2$ m was about 6% 8% and 5% for U5, U8 and U14, respectively. For the uniform fan speed cases, a lower upstream $z_0$ was found to generate a higher peak speed-up at the escarpment, with diminishing effect moving downstream. A different trend was observed for the U15 cases, where a slight reduction in peak speed-up of about 3% was observed at the escarpment for the RC2 case, with the difference between the two roughness cases slightly growing moving downstream. At M6, the lower roughness cases showed a slightly better match to the full-scale data (see Figure 2-9).

2.5.3.3 Effect of measurement and model resolution on mean flow

The Cobra Probe measurements were taken under identical fan speed and roughness element configurations as the PIV cases, although not simultaneously, and therefore from the mean flow perspective, they provide useful independent evidence for Reynolds number dependence. A comparison of speed-up ratio between PIV and Cobra Probe measurements, for the three uniform fan speed cases, for both roughness configurations, along the same vertical profile at M6, is shown in Figure 2-10. The results show good similarity between the two methods of measurements, with some systematic bias error.
resulting in slightly lower speed-up for Cobra Probe measurements, perhaps due to PIV calibration. Notwithstanding, little evidence of Reynolds number dependence is observed between the Cobra Probe profiles, confirming the trends observed earlier in the PIV data.

Figure 2-10: WindEEE PIV and Cobra Probe vertical profiles of speed-up ratio at M6, for RC1 (left) and RC2 (right).

Now turning to the discussion on the effect of model resolution on the mean flow, it is generally accepted by wind tunnel modellers that for bluff bodies submerged in deep boundary layers, Reynolds number effects are negligible for \( Re > (2-3) \times 10^4 \), particularly for flows without steady vortical regions [28]. Given that the BLWTL tests were conducted at Reynolds number above this threshold (3.6x10^4), as were the two tests conducted by Yeow et al. [17], at 4.15x10^4 and 8.21x10^4, one would expect to see Reynolds number independence preserved between normalized speed-up profiles at the BLWTL scale (1:100) and the WindEEE scale (1:25), measured using the same instrument, with similar upstream conditions. Such comparison can be made using results in Figure 2-7, which illustrates the speed-up profiles from Cobra Probe measurements at BLWTL and WindEEE. Some discrepancies are observed, particularly at M6 at \( z < 5 \) m, where WindEEE measurements were found to be higher, and closer to the full-scale
measurements. Assuming that the Reynolds number threshold [28] is applicable under present conditions, it can be concluded that the discrepancies between Cobra Probe results observed at two different model resolutions are not due to the Reynolds number but rather are caused by other factors related to model and measurement resolution such as proximity of the measurement instrument to the surface, size of the instrument relative to the model and surface roughness of the model.

2.5.4 Turbulent flow behaviour

The results for the turbulent flow are presented in a similar manner as for the mean flow behaviour in Section 5.1. To obtain a better insight into the overall turbulent flow behaviour, contour plots of the TKE increment \( \Delta \bar{k} \) over the same area as in the earlier speed-up plots, are shown in Figure 2-11a and Figure 2-11b for U14RC1 and U15RC1, respectively. A high-turbulent intensity region is observed at the escarpment, which dissipates moving downstream. Several significant differences are observed between the two cases, with U15RC1 having a larger high-intensity TKE region near the escarpment, and a longer and higher wake region. The TKE increment also begins further upstream of the escarpment. The U5 and U8 TKE contour plots (not shown) were similar to the U14 case, but with slightly lower values of \( \Delta \bar{k} \) throughout.

2.5.5 Turbulent flow comparison with previous experiments

A comparison of horizontal profiles of WindEEE TKE increment against previous experimental results, at \( z = 5 \) m and \( z = 2 \) m above surface level is presented in Figure 2-12. The two WindEEE PIV profiles stand out from the others as they feature a shallow hump between M6 and M3 at \( z = 5 \) m, and a sharp spike between the escarpment and M6 at \( z = 2 \) m. Both features are much more pronounced for the U15RC1 case compared to U14RC1. This spike was not observed by Yeow et al. [17] in PIV or hot-wire measurements, nor in the BLWTL Cobra probe or PIV results (not shown). The spike was highest for the shear profile case, but is nevertheless present to a lesser degree in all of the uniform cases, indicating fundamental differences in turbulent flow behavior between the two scales of wind tunnel experiments. These differences may be attributable
to the differences in inflow turbulence intensity between the experiments, however further investigation would be required to make definite conclusions.

![Figure 2-11: Mean TKE increment contour plot for a) U14RC1, and b) U15RC1.](image)

The Cobra Probes were not able to capture the TKE spike to the same extent as the PIV measurements, a result also evident in the vertical profile at M6 (see Figure 2-13). As was the case for speed-up ratio, the U15RC1 case was observed to better approximate the full-scale values of $\Delta \bar{k}$ than the others.
Figure 2-12: WindEEE and BLWTL TKE increment along horizontal profiles at a) $z = 5\text{m}$ and b) $z = 2\text{m}$ above surface level for PIV and Cobra Probe measurements with comparison to full-scale and to previous physical experiments.
Figure 2-13: Comparison of WindEEE and BLWTL TKE increment along vertical profiles at a) M7 ($X = -66.9$ m), b) escarpment ($X = -54.7$ m) and c) M6 ($X = -46.1$ m) with comparison to full-scale and to previous physical experiments.

2.5.6 Influence of Reynolds number, upstream roughness, inflow profile and model resolution on turbulent flow

2.5.6.1 Reynolds number and upstream wind profile effects on the turbulent flow

Figure 2-14(a,b) and Figure 2-14(c,d) show horizontal profiles of $\Delta k$ for the four wind speed cases at RC1 and RC2, respectively. The two U15 profiles stand out from the other cases, and the discrepancy is much more significant than it was for the speed-up ratio – the peak TKE increment for U15RC1 was about 200% higher than that for U14RC1. As noted earlier, the only difference between the U14 and U15 cases was the increase in the operating speed of fans in the third row by 50% compared to all other fans. This produced a slightly higher Reynolds number at the hill height for the U15 cases than for
U14, but the Reynolds number difference is only about one third of the difference between the U8 and U14 cases. Thus the difference in profile shapes at heights of \( z = 2 \) m and \( z = 5 \) m above the island appears to be attributable mainly to the induction of the strong shearing effect between fan rows 2 and 3, despite the fan row interface being about two metres off the tunnel floor in model scale, or 50 m in full-scale, more than four times the hill height. It is presumed that the additional kinetic energy imparted into the flow at the fan wall becomes mixed into the flow through turbulent transport mechanisms, and is manifested at the shear layer near the escarpment, although further analysis is required to confirm this argument.

**Figure 2-14:** Change in TKE horizontal profiles for a) RC1 cases at \( z = 5 \) m and b) RC1 cases at \( z = 2 \) m, c) RC2 cases at \( z = 5 \) m, and d) RC2 cases at \( z = 2 \) m.
There do not appear to be any indications of different behaviour between the shear and uniform cases from the inflow profiles of normalized mean wind speed and TKE profiles. The U15RC1 inflow profile is generally similar to the others in the RC1 group, regardless of which method was used to determine $u_*$, although analysis of inflow spectra may provide additional insights. While analyzing the WindEEE inflow profiles up to a height of about 100 m in full-scale would have provided a better picture of the difference in inflow conditions between the U14 and U15 cases, the comparison with upstream data from the field campaign at mast M0 at these heights not being available would preclude the interpretation of this better fit between the U15 case and full scale. Nevertheless, the results highlight the important fact that a relatively small change to the inflow wind shear profile, even well above the model height, can significantly alter the turbulent flow behaviour near the hill surface.

Among the three uniform fan speed profiles, there is little difference at $z = 5$ m, however, at $z = 2$ m, peak TKE for the U14 case between the escarpment and M6 is higher than the other two cases, for both RC1 and RC2, indicating a possible Reynolds number dependence in this region. Vertical profiles of change in TKE at M6 were also plotted (see Figure 2-15) for the RC1 and RC2 cases. The profiles for the uniform fan speed cases again tended to collapse, with the exception of the U14 cases, below $z = 2$ m, where a slight increase in TKE was observed. Consistently higher TKE is observed for the U15RC1 case, and again the U15 results are closer to the full scale data.

![Figure 2-15: Vertical profiles of TKE increment at M6 for a) RC1 cases and b) RC2 cases.](image-url)
2.5.6.2 Upstream roughness effects on the turbulent flow

The influence of upstream roughness can be seen in Figure 2-15 at M6. For the uniform fan speed cases, configuration RC2, with lower $z_0$, appeared to cause a moderate increase in TKE compared to RC1 at $z < 5$ m, while little difference in TKE was observed between the U15 cases. A comparison of horizontal profiles of RC1 and RC2 cases (not shown) showed higher TKE increment for the RC2 cases at all positions downstream of about $X = -50$ m, particularly at $z = 2$ m. The difference in peak TKE increment at different roughness configurations was about 13%, 28%, 27% at U5, U8 and U14, respectively, with the RC2 value being higher for these cases. The U15 case showed negligible difference for the two roughness cases with a weak trend of a decrease in TKE increment with the roughness. Thus, a change in the upstream roughness was observed to have an effect on the TKE for the uniform fan speed cases, while the case with modified shear profile appeared to be more resilient to changes in the roughness.

2.5.6.3 Effect of model and measurement resolution on the turbulent flow

A comparison of TKE increment between WindEEE PIV and WindEEE Cobra Probe measurements, for the same Reynolds number, and for the same vertical profile at M6 is presented in Figure 2-16. Preliminary analysis shows that this has a large effect on the flow behaviour in the region close to the top of the hill.

Strong similarity is observed between the two types of measurements, down to about $z = 3$ m, at which point some divergence is observed, with the Cobra Probes being unable to capture the spike in TKE to the same extent as the PIV measurements, which may be partially due to the reverse flow at this location. Although Reynolds number effects may contribute to the higher TKE for the U14 PIV profile at $z < 3$ m, Reynolds number independence appears to be preserved completely among the three Cobra Probe profiles all the way down. This observation once again raises the question of why the measurements of the 1:25 scale model at WindEEE are higher than those over the 1:100 BLWTL model, and why they are closer to the full-scale measurements, as seen in Figure 2-13b at M6. The resolution of the model, and the ability to measure closer to the surface
level thus appears to be one contributing factor. A separate recent study that has been submitted for publication investigates the effect of sharpening the escarpment.

![Figure 2-16: WindEEE PIV and Cobra Probe vertical profiles of TKE increment at M6, for a) RC1 and b) RC2 cases.](image)

### 2.6 Conclusions

An experimental investigation to characterize the mean and turbulent flow behaviour over a steep escarpment, represented by the topography of Bolund hill, was conducted at two distinct scales (1:100 and 1:25) by means of wind tunnel testing using Particle Image Velocimetry (PIV) and Cobra Probes. A range of Reynolds numbers, boundary layer inflow profiles, and upstream roughness values were examined. At the WindEEE research facility, three uniform fan profiles and one modified shear profile were tested at two different upstream roughness configurations, for a total of eight unique sets of inflow conditions. These results, presented in the form of normalized speed-up and TKE increment, were compared to each other and to measurements from the field campaign and previous experimental work, to attempt to establish the relative contributions of the key upstream parameters to flow behaviour over the hill.

Mean flow behaviour was found to be generally resilient to changes in upstream conditions, with negligible Reynolds number dependence observed between the uniform
fan speed cases, across a Reynolds number range of 1.7×10^5 to 4.6×10^5, for both Cobra Probe and PIV measurements. A small region of reverse flow in the mean field was detected in the separation bubble at the escarpment for all cases. Slight modification of the speed-up behaviour was observed for the shear profile case, but this did not appear to be related to the Reynolds number. Lower upstream roughness was observed to cause a marginal increase in peak speed-up at the escarpment for the uniform fan speed cases, whereas for the shear case, lower roughness caused a slight reduction in speed-up, particularly near the surface. Slightly higher values of speed-up were observed for the 1:25 scale model compared to the 1:100 model, which are attributed to factors such as proximity of the instrument to the model surface, or model surface roughness.

From the turbulent flow field data represented in the form of TKE increment, a weak Reynolds number dependence was observed whereby TKE increased with an increase in the Reynolds number, but only in the highly turbulent shear layer near the escarpment. Lower upstream roughness also served to moderately increase peak TKE among the uniform fan speed cases. A much more significant TKE increase was observed for the shear profile case, where peak normalized TKE at a height of 2 m above the hill increased by over 200% compared to the uniform fan speed case at a similar Reynolds number. Through modification of the inflow shear profile, the WindEEE facility was able to produce TKE increments that were closer to full-scale measurements, and higher than those that had been achieved previously in conventional wind tunnels, indicating a promising trend for future work in characterizing flow over topography.

For the wind developer, these results reinforce the need for very careful and detailed assessment of wind turbine inflow conditions in complex topography, as even very small changes to the inflow profile used in the modelling process can cause highly significant changes at turbine height, particularly in the turbulent flow behaviour.
References


Chapter 3

3 Analysis of turbulent coherent structures and turbulence statistics

3.1 Introduction

3.1.1 Applications and experimental techniques

The study of turbulent flow dynamics in regions of separated and reattaching flows around bluff bodies immersed in turbulent boundary layers is important in many practical applications. These include pollution dispersion, wind loads on buildings and other infrastructure such as bridges and transmission lines, as well as wind energy resource assessment and turbine loading. The physical extent of these regions and the flow behaviour within them, and the degree to which they are influenced by inflow parameters and body geometry, are currently not fully understood.

The present study involves characterization of the turbulent flow in the vicinity of a topographic feature i.e. a hill escarpment. The specific geometrical shape considered was that of the Bolund hill, which is a peninsula located near Roskilde, Denmark. It is characterized by a steep escarpment and a long flat section on top of the hill and is exposed to open fjord fetch and is used as a test case for wind resource assessment due to its similarity to a typical wind turbine site in complex topographic terrains [1]. The present study used Proper Orthogonal Decomposition (POD) to obtain a better insight into the turbulent flow structure induced by the escarpment.

Several studies have examined how steep terrains influence the incoming wind flow for wind turbine applications. Gasset et al. [2] studied the influence of a nearby coastal cliff on the power capacity of an operating wind farm. They found computational modeling of flow over a forward-facing step (FFS) to compare favourably to field measurements for mean wind speed, and in relation to cliff height $h$, the effect of the coastal cliff on the flow was found to range between $5h$ and $10h$. Sherry et al. [3] investigated flow over a FFS immersed in a turbulent boundary layer at Reynolds numbers of 1400 to 19,000 with
reference to wind energy applications, commenting on optimal placement of wind turbines relative to a cliff edge, and made use of POD analysis.

PIV measurements, often in conjunction with POD, have been shown to be effective experimental techniques to analyze complex turbulent flows around bluff bodies. Sousa [4] analyzed vortical structures around a surface mounted cube at $Re = 3210$ using two dimensional digital PIV to capture all three velocity components, Kostas et al. [5] applied POD to fluctuating velocity and vorticity fields of flow over a backward facing step at Reynolds numbers of 580 and 4660, while van Oudheusden et al. [6] investigated the mechanisms of wake formation and vortex shedding behind a 2D square cylinder using PIV and POD, including the effect of angle of incidence, at Reynolds numbers between 4000 and 20,000. Shi et al. [7] investigated the influence of wall proximity on the wake characteristics of a 2D square cylinder using POD applied to the fluctuating PIV velocity data. Although not a bluff body application, Lengani et al [8] employed POD to detect coherent structures and analyze vortex shedding in the laminar separation bubble of a turbomachinery blade using velocity data from PIV measurements.

3.1.2 Similarity of Bolund case to a Forward Facing Step (FFS)
The closest comparison between the flow around the Bolund escarpment and the canonical bluff body flow would be a forward facing step submerged in a deep turbulent boundary layer. However there are some notable differences between the actual escarpment and the simplified geometry of a step. The Bolund escarpment is not symmetric in any direction, and its surface is replete with irregularities such as bumps and crevices. Rather than having a flat face in the span-wise direction, the escarpment has more of a horseshoe shape when viewed from above. The base of the cliff resembles a ramp that ascends at an angle of roughly 50 degrees from sea level to about halfway up the escarpment height, instead of the right angle at the base of a typical step. Furthermore, rather than a sharp right angle at the leading edge, the Bolund escarpment, at least that of the model, is slightly rounded, and the curvature of the edge is also non-symmetric. The degree to which the edge of the Bolund topographical model is a faithful representation of the actual cliff edge is subject to debate, with observations of the real cliff seeming to indicate a sharper edge than what was produced based on the
topographical data [9]. An additional modeling challenge is the representativeness of the model surface roughness to that of the actual cliff, where a combination of different elements of different roughness heights, such as rock, earth and grass are present.

Yeow et al. [9] analyzed the separated flow region on the Bolund hill, using a combination of 3D hotwire, 2D PIV and pressure measurements. The results using these three methods were generally in good agreement with each other, and with many of the numerical models in the blind comparison, but in some areas inconsistent with the full-scale measurements. This was particularly the case in the vicinity of the escarpment, where both physical and numerical models have typically produced an over-estimation of speed-up, under-prediction of TKE increment, and have failed to show a region of negative flow in the separation bubble in the mean field, evidence of which was shown through field measurements using Lidar on top of the actual Bolund hill [10]. Yeow et al. [9] suggested possible reasons for the mismatch as lack of fidelity in the model reproduction of the sharp edge of the cliff, a scaling effect on behaviour of the flow, or lower levels of surface roughness on the model. Of these, the influence of the edge sharpness appears to be highly significant, and forms the subject of a dedicated separate investigation not reported here.

Despite these differences, informative comparisons can be made between the present case and the analysis of the canonical flow, and these are explored further in the discussion. To draw these comparisons, an understanding of the various features of the flow regions around bluff bodies is required. Agelinchaab and Tachie [11] effectively summarize these regions and the associated characteristic lengths typical of bluff bodies exposed to boundary layer flow. These include an initial point of flow separation, one or more separation bubbles and recirculation zones, a shear layer above the body, a reattachment point downstream of the body, and further downstream, a recovery region where a new boundary layer forms, which with sufficient distance from the body, often returns to similar but not necessarily identical form as the original inflow profile.
3.1.3 Response of resultant turbulent flow behaviour to input stimuli

A common and valuable means of investigating complex turbulent flows is through the analysis of the response of the flow behaviour to changes in input conditions [12]. Several investigations of flow around a FFS have examined the effect of various changes to inflow conditions and body geometry on the turbulent flow behaviour in the separation and reattachment regions, and are worth summarizing given their relevance to the present study. Bowen and Lindley [13] studied turbulence characteristics of flow across two-dimensional forward facing escarpments of different angles of inclination. They found that once the angle was steep enough to cause flow separation (> 30°), mean flow behaviour was fairly insensitive to increased steepness, however turbulence intensity and extent of the wake region increased with slope angle, and that high turbulence was effectively limited to the wake region. Tachie et al. [12] investigated relaxation lengths in the wake of a FFS at low Reynolds number (Re) and found recovery of turbulence intensity profiles \((x/h >= 100)\) to be much slower than those of the mean flow \((x/h > = 50)\), and different rates of recovery for the viscous sublayer, outer layer and overlap layers. Taylor et al. [14] examined the flow around elongated bluff bodies with the same chord to thickness ratio but distinct leading and trailing edge geometries, at a Reynolds number of \(3 \times 10^4\), and showed that these geometric differences had significant effects on reattachment length, vortex shedding frequency and wake characteristics.

Largeau and Moriniere [15] examined flow over a forward facing step using flow visualization and PIV techniques in a wind tunnel at higher Reynolds numbers \((2.88 \times 10^4 \text{ to } 12.82 \times 10^4)\), i.e. closer to the range of the present study. They provide an excellent description of three dimensional vortex structure and dynamics present in the flow and physics of fluid motion related to flow separation. Camussi et al. [16] investigated the effect of Reynolds number on flow over a FFS across a Reynolds number range of 8800 to 26,300 using 2D PIV, and found that Reynolds number affected the size and intensity of the recirculation region downstream of the leading edge. Similar studies using numerical methods have also been conducted. Lamballais [17] used Direct Numerical Simulation (DNS) to study flow over 2D and 3D forward facing steps with rounded
leading edges. They found that the edge curvature has a significant effect on the separation bubble dynamics. Perhaps counter-intuitively, higher edge curvature was shown to increase turbulent kinetic energy in the bubble region. They also showed that higher levels of inflow perturbation (increased turbulence intensity) had the effect of shortening the height and reducing the length of the separation bubble. Finally, Hattori and Nagano [18] present mean and turbulent profiles from DNS of flow over a forward facing step at three Reynolds numbers (900, 1800, 3000) and two step heights. They also present profiles of Reynolds shear stress budgets conduct quadrant analysis which shows the dominant motion of shear stress production over the step.

3.2 Methodology

3.2.1 Experimental setup

The experiment was conducted at Western University’s Wind Engineering, Energy and Environment (WindEEE) dome [19], a unique large-scale multi-fan wind research facility that can be operated in several modes. The present investigation was conducted under straight-flow configuration, where a matrix of 60 fans (4 rows × 15 fans/row) along one wall of the hexagonal chamber, each with 30 kW nominal power, were used to generate wind flow. A contraction section was attached to the fan wall in order to increase wind speed in the test section and improve flow uniformity. Equipment used to generate the boundary layer profiles included a trip, spires, and roughness elements with height of 7.5 cm. Two different upstream roughness configurations, RC1 and RC2, were used during the experiment, by manipulating the heights of the roughness elements (7.5 cm full height) installed between the contraction section and the turntable. RC1 corresponds to the higher roughness case where all roughness elements were fully raised, whereas RC2 produced lower effective roughness height by fully lowering one block of about 80 elements immediately upstream of the turntable.

A 1:25 scale model of the Bolund hill was constructed through CNC milling of expanded polystyrene (EPS) blocks, according to topographic data, and then glued together. The completed model measured roughly 4.5 m wide, 0.5 m high, and 3.5 m long. During the experiment, the model was positioned on the turntable such that it coincided with the
270° wind direction during the Bolund field measurement campaign [1] and, hereinafter referred as Line B. The escarpment leading edge was roughly 12.4 m from the fan wall.

Instantaneous velocity fields in the region of the escarpment were captured by using the Particle Image Velocimetry (PIV) technique. Images were acquired from three 12 megapixel cameras (IO Industries Flare 12M125-CL), each with 105 mm f/2D Nikon AF DC-NIKKOR lenses, positioned in a row parallel to the flow direction at a distance of 3.55 m from Line B. The cameras each had resolution of 4096 × 3072 pixels, yielding a field of view of about 0.78 m wide by 0.58 m high. At least 10% overlap was used between cameras, resulted in a combined coverage area of roughly 2.09 m wide by 0.58 m high. PIV images were recorded at a rate of 18 Hz, or 9 Hz for image pairs for duration of between 3 and 5 minutes, depending on the test case, yielding 1800-2700 image pairs.

A Litron Nano Piv Series dual cavity Nd:YAG laser (wavelength 532 nm, energy 425 mJ/pulse), synchronized to the image acquisition system (IO Industries Coreview), was used to illuminate the flow field. The laser was positioned behind the model, facing upstream, and a 50° cylindrical lens was attached to the laser head to produce a two-dimensional light sheet. Seeding of the chamber was accomplished by means of a commercial fog generator (Ultratec CLF-4460) located in the dome’s upper plenum.

Post-processing of PIV was accomplished using the Heurisko® (AEON Verlag & Studio GmbH & Co. KG) image processing software with an in-house algorithm. Interrogation windows (128 pixels) in the first image of the image pair were cross-correlated with the search windows (64 pixels) in the second image to generate the instantaneous velocity fields. Grid spacing was set at 16 pixels to increase the nominal resolution of the velocity field. A local median test by Siddiqui et al. [20] was used to identify and correct spurious vectors. Mean \((U, W)\) and turbulent \((u', w')\) fields were then calculated using in-house codes in the Matlab environment, by averaging instantaneous \((u, w)\) velocity components at each grid point over the sampling time, and subtracting the mean fields from the instantaneous velocity fields, respectively.
3.2.2  **Inflow conditions**

Reference inflow conditions were measured at a position 2.25 m upstream of the model escarpment edge by means of a floor—mounted vertical array of eight Cobra probes with acquisition rate of 10,000 Hz, output rate of 1250 Hz, and sampling time of 120 seconds. Cobra probes (Turbulent Flow Instrumentation Pty Ltd.) are dynamic multi-hole pressure probes for measuring all three components of mean and fluctuating velocities and static pressure. Extrapolation of upstream profiles from the Cobra probe heights to the PIV grid heights was performed using the logarithmic law, given as [20]:

\[
\frac{U(z)}{U(z_r)} = \ln \left( \frac{z}{z_0} \right) / \ln \left( \frac{z_r}{z_0} \right)
\]  

where \( z_r \) is the reference height and \( z_0 \) is the roughness height.

The streamwise velocity profile data within the logarithmic region was fitted to the standard logarithmic wind profile for neutral stability conditions to obtain friction velocity and effective roughness using the following equation [20]:

\[
U(z) = \frac{u_*}{\kappa} \ln \left( \frac{z}{z_0} \right)
\]

where \( z \) is the vertical height from the ground, \( U(z) \) is the streamwise wind speed at that height, \( u_* \) is the friction velocity, and \( \kappa \) is the von Karman constant taken as 0.41. Table 1 shows the relevant test parameters for the present experiment. Ten different test cases were selected, each with a unique combination of inflow conditions and model geometry, with the intent of identifying how such changes affect the resulting flow behaviour. Cases are identified by the upstream wind speed at hill height (i.e. \( U5 \sim 5 \text{ m/s} \)) and roughness configuration (RC1 or RC2). Eight cases have uniform fan speed, such that all 60 fans were operating at the same speed. The other two cases (U15RC1 and U15RC2) have a modified shear profile, where fans in row 3 were operated at 50% higher RPM than the fans in other three rows (for reference, fan row 1 is at the floor level). Four cases used roughness configuration RC1, while the other six used RC2, where the RC2 cases have a lower effective roughness \( z_0 \), as mentioned earlier. Cases with the same fan arrangement but different roughness configurations (i.e. U5RC1 and U5RC2) had almost identical
Reynolds number, but different roughness lengths and friction velocities. Two cases (U8RC2S and U14RC2S) had a modified escarpment edge, where modeling clay was placed along the leading edge of the model to produce a sharper edge as per discussion in Section 2.1. The sharp-edge cases had identical inflow conditions as their rounded-edge counterparts i.e. U8RC2 and U14RC2, respectively.

**Table 3-1: WindEEE test parameters and inflow conditions**

<table>
<thead>
<tr>
<th>Case ID</th>
<th>Fan configuration</th>
<th>Model edge</th>
<th>$\bar{u}_b$ (m/s)</th>
<th>Re</th>
<th>$z_0$ (m)</th>
<th>$u_*$ (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>U5RC1</td>
<td>All fans 20%</td>
<td>Round</td>
<td>5.42</td>
<td>$1.70 \times 10^5$</td>
<td>$1.84 \times 10^{-3}$</td>
<td>0.254</td>
</tr>
<tr>
<td>U5RC2</td>
<td>All fans 20%</td>
<td>Round</td>
<td>5.49</td>
<td>$1.72 \times 10^5$</td>
<td>$1.96 \times 10^{-6}$</td>
<td>0.145</td>
</tr>
<tr>
<td>U8RC1</td>
<td>All fans 30%</td>
<td>Round</td>
<td>8.70</td>
<td>$2.72 \times 10^5$</td>
<td>$1.98 \times 10^{-3}$</td>
<td>0.409</td>
</tr>
<tr>
<td>U8RC2</td>
<td>All fans 30%</td>
<td>Round</td>
<td>8.57</td>
<td>$2.68 \times 10^5$</td>
<td>$4.12 \times 10^{-7}$</td>
<td>0.203</td>
</tr>
<tr>
<td>U8RC2S</td>
<td>All fans 30%</td>
<td>Sharp</td>
<td>8.57</td>
<td>$2.68 \times 10^5$</td>
<td>$4.12 \times 10^{-7}$</td>
<td>0.203</td>
</tr>
<tr>
<td>U14RC1</td>
<td>All fans 50%</td>
<td>Round</td>
<td>14.60</td>
<td>$4.57 \times 10^5$</td>
<td>$2.72 \times 10^{-3}$</td>
<td>0.723</td>
</tr>
<tr>
<td>U14RC2</td>
<td>All fans 50%</td>
<td>Round</td>
<td>14.69</td>
<td>$4.60 \times 10^5$</td>
<td>$2.29 \times 10^{-6}$</td>
<td>0.392</td>
</tr>
<tr>
<td>U14RC2S</td>
<td>All fans 50%</td>
<td>Sharp</td>
<td>14.69</td>
<td>$4.60 \times 10^5$</td>
<td>$2.29 \times 10^{-6}$</td>
<td>0.392</td>
</tr>
<tr>
<td>U15RC1</td>
<td>Fan rows 1,2,4: 50%, Fan row 3: 75%</td>
<td>Round</td>
<td>15.60</td>
<td>$5.21 \times 10^5$</td>
<td>$2.87 \times 10^{-4}$</td>
<td>0.650</td>
</tr>
<tr>
<td>U15RC2</td>
<td>Fan rows 1,2,4: 50%, Fan row 3: 75%</td>
<td>Round</td>
<td>~15.60</td>
<td>~$5.21 \times 10^5$</td>
<td></td>
<td>Not measured</td>
</tr>
</tbody>
</table>
3.3 Results and discussion

3.3.1 Proper orthogonal decomposition (POD) analysis

Proper orthogonal decomposition (POD) is a technique for analyzing energetic flow patterns in a turbulent flow, which helps to gain better insight into the coherent structures present. Originally proposed by Lumley [22], this method can be used to observe the energy distribution of the flow at different orthogonal modes. Lower modes are associated with larger and more dominant flow patterns, and as the mode number increases, the size and energy of the flow patterns decrease accordingly. While the POD field at each mode presents the spatial distribution of the corresponding flow energy, previous studies have shown that these flow energy patterns are related to the physical flow structures present in the flow. For example, Meyer et al. [23] observed POD modes to be consistent with vortices in the wake of a jet. The study by Maurel et al. [24] with regards to jet/vortex interaction in an internal turbulent flow showed maximum energy of the modes and the vortex to be directly correlated. Other studies have also reported similar relations between the prominent flow structures and the POD modes (Régert et al.[25]; Basley et al. [26] and Podvin et al. [27]).

In the present analysis, the snapshot method, developed by Sirovich [28], whereby turbulent velocity fields are treated as snapshots of the flow, was used to detect and characterize the underlying flow patterns in the flow over the escarpment and to study the influence of various parameters on the energy distribution and flow energy patterns. A POD algorithm developed by Doddipatla [29] was used to decompose the turbulent flow data into its orthogonal modes or basis functions where the expansion of the velocity \( \bar{u}(\bar{x}, t) \) into spatial and temporal coefficients is represented by:

\[
\bar{u}(\bar{x}, t) = \sum_{n=1}^{N} a^n(t) \phi^n(\bar{x})
\]  

(3.3)

Where \( a^n(t) \) is the temporal coefficient and \( \phi(\bar{x}) \) is the spatial component or basis function [30]. In the present analysis the POD data is based on 1200 snapshots for the rounded edge cases and 900 for the sharp edge cases. The code has been validated by earlier studies [31, 32].
Figure 3-1 shows the energy contained in each mode as a fraction of the total flow energy, at different upstream conditions as well as modified model escarpment edge. As expected, most of the POD energy is contained in the lower modes, with fractional energy decaying rapidly in higher modes. For all of the cases with the original rounded escarpment edge, modes 1 and 2 combined represented between 17-20% of total POD energy contained in all modes, with modes 3-10 accounting for another 20-25% of the total energy.

A clear distinction in energy distribution was observed for the two sharp edge cases (see Figure 3-1b), where the fractional energy in mode 1 alone was around 8% and 20% for U8RC2S and U14RC2S, respectively. For these cases, mode 3 had lower energy than the others. The uniform fan speed cases (U5, U8 and U14) had generally similar fractional energy distributions, with minor differences noted for modes 2 and 3. The U15 cases, compared to the other rounded edge cases, showed higher fractional energy in mode 1, similar energy in modes 2-3, and lower energy in modes 4-6, before the distribution curves for all cases collapsed around mode 10.

When comparing the same Reynolds numbers at two different upstream roughness configurations (i.e. RC1 vs. RC2 cases), the main difference was observed in the first mode, where fractional energy was lower for the lower roughness RC2 cases with uniform fan speed (U5, U8 and U14). The trend however was opposite for U15 where the fractional energy in the first mode at lower roughness was higher than that for the higher roughness. As mentioned in Section 2.2, for U15 cases, the speed of the fans in the third row fans was 50% higher than the fans in rows 1, 2 and 4. Hence, the U15 case simulates an upstream condition where additional inertia and consequently shear is added to the flow at a height of roughly four times hill height h. This added shear is manifested in the higher energy at mode 1 at both roughness cases for U15. The lower flow energy or inertial effects under higher upstream roughness conditions (U15RC1) may be due to the reason that lower roughness causes less vertical mixing and hence the added inertia is more significant for the U15RC2 case.
Figure 3-1: POD fractional energy for a) RC1 and b) RC2 cases

Figure 3-2 shows contours of normalized streamwise POD energy $\phi(\bar{x})$, at various modes at different upstream wind conditions and surface roughness. Note that the edge of the escarpment is used as the origin in the spatial coordinate system and each coordinate is scaled by the hill height $h$. For all cases, the general trends are relatively similar. That is, the first three modes tend to depict larger bulk motions, while higher modes (i.e. modes > 30) show smaller scale turbulent features. Intermediate modes, combined through linear summation (i.e. modes 9-11, 14-16 etc.), show clearly the formation of coherent structures, indicated by alternating positive and negative POD energy patterns.

The highest energy-containing regions in the low-to-mid mode range occur within the separation bubble just downstream of the escarpment leading edge, indicating that the coherent structures emerged from the edge of the escarpment where the separation bubble initiated. A reduction in energy then takes place moving further downstream. Contours for cases U5RC1 (Figure 3-2a) and U14RC1 (Figure 3-2b) are quite similar. These cases represent the change in wind speed and the Reynolds number while other upstream conditions remained the same.

The comparison shows that although the trends are similar, the scale of the flow energy patterns increased with an increase in the Reynolds number. This is expected as the increase in Reynolds number influences the ratio of largest to smallest eddies. The similarity of flow energy patterns at different modes for these two cases indicates that
over the escarpment, the turbulent flow patterns at different scales have no strong
Reynolds number dependence.

The comparison of cases U14RC1 (Figure 3-2b) and U14RC2 (Figure 3-2c) that
correspond to the change in upstream roughness show some variations particularly in the
intermediate mode range where the flow energy patterns are relatively larger at higher
upstream roughness and smaller and relatively more energetic at lower upstream
roughness. Notable differences are observed for the U15RC1 case (Figure 3-2d), where
the POD energy contours in mode 1 show a much different flow energy distribution than
for any of the other uniform flow cases.

Furthermore, the vertical extent of the vortices in modes 4-5, 6-8 and 9-11 is greater than
for the other cases. The vertical extent of energetic flow patterns reached almost 50% of
the escarpment height for $x/h > 2$. These results indicate that the additional upstream
shear induced larger coherent structures within the separation bubble.

The results at higher modes in the above mentioned cases show that the flow energy
patterns are relatively weak and much smaller in size, as expected. It is also observed that
the most energetic flow patterns were mainly confined in the region close to the
escarpment edge near the surface (within $x/h \approx 2$) and they lose energy rapidly as then
move further downstream. Comparison at different upstream conditions show that the
trends at higher modes are relatively similar to those observed in lower and intermediate
modes.

The most significant differences in POD energy patterns were observed for the sharp
dege cases (i.e. Figure 3-2e). Fundamental differences can be seen at the lowest modes,
where the shape of the patterns are more circular, an indication of the flow separating off
of the leading edge of the escarpment at a sharper angle. In the intermediate modes,
unlike the round edge cases, the highest energy patterns occur well above the hill surface.
The vertical extent of the energetic flow patterns almost reached the hill height at $x/h \sim 2$
and continued to extend further beyond this streamwise distance.
Figure 3-2: Contours of streamwise POD energy $\phi^u(\bar{x})$, for cases a) U5RC1, b) U14RC1, c) U14RC2, d) U15RC1 and e) U14RC2S
Results in Figure 3-2 provided representations of qualitative behaviour through various POD modes for different inflow cases. This information is vital to obtain a better insight into the dynamics and characteristics of coherent structures embedded in the turbulent flow field in the vicinity of an escarpment. These results indicate that the strongest coherent structures are present within the separation bubble formed due to the flow separation off the escarpment edge. The results also show that the changes in the inflow conditions mainly influence the size of energetic coherent structures in the low to intermediate range. However, the modification of the escarpment edge has the most profound effect on the scale of coherent structures and their extent. To further understand the turbulent flow behaviour, various turbulent characteristics were computed and analysed to investigate and quantify the influence of different conditions on the turbulent flow over the escarpment.

3.3.2 Reynolds stress

Figure 3-3 shows contours of normalized Reynolds shear stress $-\overline{uw}/U_h^2$ with streamlines of mean velocity overlaid, for the same five cases presented in Figure 3-2. Streamlines show distinct mean flow behaviour for the round edge cases (i.e. Figure 3-3a–d), where streamlines are all quite similar, in contrast to the behaviour of the sharp edge case (Figure 3-3e). Streamlines for the sharp edge case show a much larger separation bubble than the round edge cases, with a clearly visible recirculation region. Although not readily apparent from the streamlines, the rounded edge cases do have a small region of reversed flow immediately downstream of the escarpment edge.

Through a rough measurement of the reattachment point i.e. the location near the surface where the flow changes from reverse flow to forward flow [14], the reattachment length is estimated to be approximately $x_r/h = 2.1$ for the sharp edge case compared to only about $x_r/h = 0.25$ for the round edge cases. The height of the separation bubble reaches about $y/h = 1.25$ for the sharp edge, compared to only about $y/h = 1.05$ for the round edge. Furthermore the separation angle $\alpha$ was much steeper for the sharp edge cases. Taking separation angle to be the angle between the streamwise direction and the tangent to the streamline at the separation point [14], $\alpha$ was estimated to be roughly $\sim 70^\circ$ for the sharp edge cases and $\sim 35^\circ$ for the round edge cases.
The highest Reynolds shear stress occurred at different locations for the round edge and
sharp edge cases. For the rounded edge cases, with a very small separation bubble, as
seen from the mean streamlines, the peak magnitude of Reynolds stress occurred in the
region immediately downstream of the escarpment. This was also near the region of
highest mean streamwise wind speeds, which occurred just above the escarpment edge at
\((x/h \approx 0, y/h \approx 1.1)\). For the sharp edge case however, with a much larger separation
bubble and where the highest mean streamwise speeds are located at \((x/h \approx 0.6, y/h \approx
1.5)\), the high stress region is seen further downstream and at a higher vertical position,
which covered a much larger area. All cases showed negative shear stress values near
\(x/h = 0\), consistent with previous analyses of flow over a forward-facing step across a wide
range of Reynolds numbers [3, 15, 18].

Among the round edge cases, comparison of the results at different inflow conditions
show that the change in Reynolds number did not have any significant influence on the
Reynolds stress magnitude and distribution (Figure 3-3a & b). The change in the
upstream roughness appeared to have a small impact on the Reynolds stress magnitude
(Figure 3-3b & c). For cases with lower upstream roughness, Reynolds stress magnitudes
were higher in the immediate downstream region of the escarpment edge, and the height
of the strong Reynolds stress layer was also slightly larger as compared to the case with
higher upstream roughness. However, in the region immediately upstream of the
escarpment edge, the Reynolds stress magnitude for the lower roughness case is lower
than that of the higher roughness case.

The results however show a significant change in the Reynolds stress magnitude and
distribution when the additional shear and inertia was added to the upstream flow (case
U15). The results in Figure 3-3d show that this variation in the upstream condition not
only increased the magnitude of Reynolds stress both upstream and downstream of the
escarpment edge but also significantly increased the vertical extent of the strong
Reynolds stress layer, reaching a distance of close the escarpment height above the
surface by \(x/h = 3\). The results also show a substantial shift in the peak Reynolds stress
away from the surface.
As discussed, the sharp edge cases showed distinct Reynolds stress distribution compared to the round edge cases. Reynolds stress contours for the sharp-edge U14RC2S (Figure 3-3e) are highly similar to those observed by Sherry et al. [3] for flow over a FFS at $Re = 6741$. Common features include the strong negative stress region emerging from the escarpment edge at roughly the same angle (~$60^\circ$ from horizontal), and the streamline dividing the separation bubble from the main flow roughly bisecting the region of peak shear stress, which for U14RC2S has a centre-point of roughly ($x/h = 1.5$, $y/h = 1.3$). Peak normalized shear stress for the U14RC2S case was 0.070, closely matching the levels observed by Sherry et al. at the centre of the high intensity region.
Figure 3-3: Contours of Reynolds shear stress with mean streamlines overlaid, for cases a) U5RC1, b) U14RC1, c) U14RC2, d) U15RC1, and e) U14RC2S.

For a quantitative comparison between cases, vertical profiles of Reynolds stress at different axial locations are plotted in Figure 3-4, again highlighting the differences between inflow conditions and leading edge geometry. The results in Figure 3-4 (a, b)
show the Reynolds stress profiles for cases with higher and lower upstream roughness, respectively. The results show that for the same uniform upstream conditions (U5, U8 and U14) the Reynolds stress profiles collapsed very closely indicating that variation of the Reynolds number across this range does not have any significant influence on the Reynolds stress behaviour in the flow around the escarpment. The same behaviour is observed under both roughness conditions.

As indicated earlier, the results in Figure 3-4 quantitatively confirm that the modified upstream shear profile acts to significantly increase the magnitude and extent of the Reynolds stress over the escarpment. The results show that the peak magnitude of normalized Reynolds stress at $x/h = 0.5$ for the U15 cases compared to the average of the three uniform flow cases is 120% higher for RC1 and 130% higher for RC2. Comparison of the results at two different roughness conditions show that in general, the Reynolds stress magnitude is slightly higher for the lower roughness case at all wind speeds, as discussed.

The much higher Reynolds stresses induced by the sharp edge are clearly visible in Figure 3-4b. The shear stress profiles of the sharp edge cases also more closely resemble those of the canonical flow over a forward facing step. Results obtained by Hattori and Nagano [18] using DNS are shown for comparison purposes, for one of their investigated cases where $Re = 3000$, and the step height was equal to three times the inlet momentum thickness ($h = 3\delta_{2,in}$). Profiles between $x/h = 0.5$ and $x/h = 2$ show similar trends, with peak stress occurring at roughly the same height, however the magnitudes are higher for the WindEEE cases. Although not visible on the plot given the scale of the axis, the Hattori and Nagano [18] results show negative Reynolds stresses around $y/h = 1.04$, although the highest negative values of roughly -0.016 are lower than those for the sharp edge cases, i.e. -0.052 for U8RC2S and -0.049 for U14RC2S.
3.3.3 Turbulence intensity

In Figure 3-5, contours of streamwise turbulence intensity $u'^2$ normalized by the square of incoming wind speed at hill height $U_h$ are plotted to further analyze the changes to the turbulent behaviour for different test cases. Given the high inflow turbulence at the large scale WindEEE facility (~0.13 for the present study) compared to typical wind tunnels, the minimum contour was set to 0.15 to highlight the increase in turbulence due to the presence of the hill. Similar to previous results, turbulence intensity contours for U5 (Figure 3-5a) and U14 (Figure 3-5b) are almost identical, indicating little Reynolds number dependence across this range. Upstream roughness appears to have only a minor

Figure 3-4: Vertical profiles of Reynolds shear stress for a) RC1 cases, and b) RC2 cases
effect, with lower roughness serving to slightly increase turbulence intensity downstream of the escarpment (i.e. Figure 3-5b and Figure 3-5c).

Among the uniform flow cases, the modified shear profile had a significant effect, where the U15 cases (i.e. Figure 3-5d) showed overall higher magnitudes of turbulence intensity, with the wake extending both further downstream and higher in the vertical direction than for the other cases. A comparison between the round edge (i.e. Figure 3-5c) and sharp edge (i.e. Figure 3-5e) configurations for the same inflow conditions show very different distributions. For the round edge case, turbulence intensity is more concentrated in a small area near the escarpment, with very high peak values. For the sharp edge case, the overall peak is moderately lower, but the disturbance is spread out over a much larger area.
Figure 3-5: Contours of streamwise turbulence intensity for cases a) U5RC1, b) U14RC1, c) U14RC2, d) U15RC1 and e) U14RC2S.
Figure 3-6 presents vertical profiles of normalized streamwise turbulence intensity for both roughness cases. The upstream turbulence intensity at hill height was subtracted in order to facilitate comparison to other work. Among the uniform fan speed cases, profiles collapse closely for both roughness configurations, with a small amount of variability observed in the highly turbulent region close to the escarpment at $0 < x/h < 1$ and $y/h < 1.2$. For these cases, lower upstream roughness caused a slight shift to the right, as mentioned.

Figure 3-6: Vertical profiles of streamwise turbulence intensity, normalized by incoming wind speed at hill height for a) RC1 cases, and b) RC2 cases. Inflow turbulence intensity removed for comparison. Some values removed from top of $x/h = 0.5$ profile due to poor data quality.
The significant increase in turbulence intensity due to the modified shear profile is clearly observed in the results, with this case producing about 85% higher peak turbulence intensity at $x/h = 0.5$ than the average of the three uniform flow cases for both RC1 and RC2 cases.

Also plotted in Figure 3-6b are the DNS results from Hattori and Nagano [18] for the same case introduced above. The DNS profiles show high similarity in both the shape of the profiles as well as the normalized magnitudes to those obtained in the present study for the sharp edge cases. The heights where peak turbulence intensity occur are also nearly identical. Interestingly, the vertical extent of the disturbed region for the DNS cases is larger than that of the sharp edge cases. The profiles at $x/h = 1$ and $x/h = 1.5$, for example, show turbulence intensity well above inflow levels at $y/h = 2$ for the DNS case, whereas it has returned to inflow levels at this height for the present sharp edge case. Nevertheless, in terms of the turbulence intensity profiles, the sharp edge cases are clearly better approximations to the FFS flow case.

### 3.3.4 TKE production

Two important components of the overall turbulent kinetic energy (TKE) budget are the production and dissipation terms. The TKE production term measures the rate at which kinetic energy is transferred from the mean flow to the fluctuating velocity field, and was calculated for each test case in the streamwise direction as per Pope [33]:

$$ P = -u' w' \frac{\partial u}{\partial y} \quad (3.4) $$

The contours of TKE production, normalized by $U_h^3/h$ are shown in Figure 3-7 for the same cases shown earlier. The trend of TKE production was in general found to be similar for all cases. That is, the highest production rate is observed in the region immediately downstream of the escarpment edge, and the TKE production rate decreased with an increase in the downstream distance, while the vertical extent increased with the downstream distance. The results also show regions of negative TKE production, which occur where the mean gradient and the Reynolds shear stress have opposite signs. The largest negative values occur in the strong speed-up region where the flow first passes the
escarpment leading edge. In this region, the mean velocity gradient is still positive, but the Reynolds stresses are negative, leading to the negative TKE production. The negative TKE production also occurred to a lesser degree in the vertical zone above the speed-up region, where the mean gradient is negative, but Reynolds stress is positive.

Comparison of the results at different inflow conditions show that the trends are in general similar to those observed for the Reynolds shear stress. That is, the rate of TKE production is very similar when the Reynolds number changed while other conditions were kept constant (Figure 3-7a & b).
Figure 3-7: Contours of streamwise TKE production $P$ for cases a) U5RC1, b) U14RC1, c) U14RC2, d) U15RC1 and e) U14RC2S.

A slight increase in the TKE production rate was observed when the upstream roughness was lower (Figure 3-7b & c). Similarly, the increase in the shear and inertia of the upstream wind significantly increased the magnitude and extent of the TKE production.
(Figure 3-7d). The sharp edge case (Figure 3-7e) again shows distinctive behaviour from the others, where the region of high TKE production is located further downstream and higher in the vertical direction, and occupies a much larger region, analogous to the distribution observed for the Reynolds stress contours.

Vertical profiles of the normalized streamwise TKE production rate at different axial locations are plotted in Figure 3-8 under different conditions for quantitative comparison. Profiles of TKE production generally show similar behaviour as Reynolds shear stress profiles in Figure 3-4, a result also observed by Agelinchaab and Tashie [11] in their study of flow over surface mounted blocks.

Similar to the Reynolds stress case, the results show that for the same uniform upstream conditions (U5, U8 and U14) at a given upstream roughness, the TKE production profiles collapsed very closely indicating Reynolds number independence. Comparison of the results at two different roughness conditions show that in general, the magnitude of TKE production rate is slightly higher for the lower roughness case at all wind speeds.

TKE production for U15 was significantly higher in magnitude and extent compared to the cases with uniform upstream wind condition. In the region of intense TKE production rate ($x/h \sim 0.5$), the normalized peak TKE production rate is about 320% and 260% higher than the uniform flow cases for RC1 and RC2, respectively. Whereas further downstream, the peak has shifted away from the surface for U15 and the differences are much smaller, approximately 36% higher for RC1 and 50% higher for RC2 at $x/h = 2.5$. The shape of the profiles for the sharp edge cases was again observed to be completely different, with peak values occurring well off the surface, analogous to the Reynolds stress profiles.
3.3.5 TKE dissipation

In separated flows, diffusion acts to transport turbulent kinetic energy from the middle layer to the outer and near-wall regions, and its magnitude has been shown to be a non-negligible component of the overall energy budget [11]. Doron et al. [34] showed that the direct estimation of the rate of TKE dissipation ($\varepsilon_D$) using velocity gradients computed from the two-dimensional turbulent velocity field obtained from PIV measurements was the most accurate among five different methods they investigated. Following their approach, the rate of TKE dissipation was computed using the following equation [34],

**Figure 3-8**: Vertical profiles of TKE production for a) RC1 cases, and b) RC2 cases. Extreme negative values at $x/h = 0$ omitted to facilitate plotting.
\[ \varepsilon_D = 3\nu \left[ \left( \frac{\partial u}{\partial x} \right)^2 + \left( \frac{\partial w}{\partial y} \right)^2 + \left( \frac{\partial u}{\partial y} \right)^2 + \left( \frac{\partial w}{\partial x} \right)^2 + 2 \left( \frac{\partial u}{\partial y} \frac{\partial u}{\partial y} \right) + \frac{2}{3} \frac{\partial u}{\partial x} \frac{\partial w}{\partial y} \right] \]  

(3.5)

where, \( \nu \) is the kinematic viscosity of air.

Contours of the normalized TKE dissipation rate are shown in Figure 3-9 for the same cases shown earlier. The results show a similar trend for all cases i.e. the rate of TKE dissipation is highest in the vicinity of the escarpment edge and its magnitude decreases in the downstream direction. The strong TKE dissipation magnitudes were mainly restricted close to the surface for the uniform flow cases, whereas for the sharp edge case (Figure 3-9e), the high dissipation region was formed away from the surface, roughly following the streamlines for that case. The plots also show that the extent of the dissipation region is much smaller than the production region.
Figure 3-9: Contours of TKE dissipation for cases a) U5RC1, b) U14RC1, c) U14RC2, d) U15RC1 and e) U14RC2S.
The vertical profiles of TKE dissipation rate at different downstream locations are shown in Figure 3-10. As observed, uniform flow cases showed similar trends in terms of the profile shape, and a similar order of magnitude increase for peak dissipation at $x/h = 0$. The results also show a decreasing trend in the TKE dissipation rate with an increase in Reynolds number for the uniform upstream wind cases. This indicates a possible weak dependence of the TKE dissipation rate on Reynolds number, although given the similar shape of the profiles the differences may be related to choice of normalizing variable.

Figure 3-10: Vertical profiles of TKE dissipation for a) RC1 cases, and b) RC2 cases. Note log scale on x-axis. Some values removed from the tops of profiles at $x/h = -0.5$ through $x/h = 1$ due to poor data quality.
Furthermore, the increase seen in Reynolds stress and TKE production magnitudes for the U15 cases is not evident for the dissipation rate. The results at different upstream roughness configurations show no significant difference, indicating that the dissipation rate has no dependency on the upstream roughness. Comparison of the TKE production and dissipation rates show that over the escarpment edge and in the downstream region over the escarpment, the TKE production rate is much higher than the TKE dissipation rate.

The two sharp edge cases showed similar dissipation rate profiles to each other, again confirming Reynolds number independence even with different leading edge geometry, however they do show differences to the round edge cases, primarily in the region of $0.5 < x/h < 2$.

### 3.4 Discussion

The results of the investigation indicate that, with a sharp leading edge, a valid approximation of the flow over the escarpment can be made to flow over a forward-facing step. The size of the separation bubble, the reattachment length and the turbulence intensity and Reynolds stress profiles seen for the sharp edge cases match much more closely to the results of previous work on FFS flow than for the round edge cases. These similarities were observed despite the many differences noted in the introduction between the irregular three-dimensional escarpment topography of the Bolund hill and the canonical forward-facing step. The dimensions of the separation bubble clearly have a strong influence on the dynamics of the overall flow behaviour, as it significantly affects the shear stress distribution. Changes to Reynolds number, upstream roughness and shape of the inflow shear profile had almost no effect on the size of the separation bubble nor to proximity of FFS flow. Thus the leading edge geometry appears to be one of the governing factors in producing topologically similar flow behaviour.

It is of interest to note that a large separation bubble can still be achieved over a FFS, even with a high radius of curvature on the leading edge. Using DNS, Lamballais et al. [17] investigated the size of the separation bubble over a FFS with varying degrees of leading edge curvature, as well as varying degrees of inflow perturbation. They showed
that a large separation bubble was produced even for a step with radius of curvature equal to the step height (i.e. much larger than the round edge cases in the present study). However, this result was obtained with very low inflow turbulence level. When the inflow perturbations were increased, the size of the separation bubble shrunk accordingly. The smallest separation bubble was observed for the case where both radius of curvature and inflow perturbation were highest. Thus in the present study it may be the combination of the rounded edge and high inflow turbulence that act together to suppress the formation of a large separation bubble for the round edge cases.

3.5 Conclusions

An experimental study was undertaken to characterize the influence of upstream parameters and shape modification on the underlying structure of turbulent flow over an escarpment. The experiments were conducted on a 1:25 scale model of Bolund hill in Denmark, which has been used as a field test site to study the flow modification by complex topography. Particle Image Velocimetry (PIV) was used to measure the flow in the vicinity of the escarpment and the in-depth investigation of the turbulent flow structure was conducted using Proper Orthogonal Decomposition (POD) technique. Parameters varied in this study included Reynolds number, upstream roughness, shape of the inflow shear profile and the curvature of the escarpment leading edge. The results show that in general, Reynolds number had little effect on the turbulent flow behaviour over the escarpment. The upstream roughness was found to have a weak but repeatable effect where lower roughness contributed to a slight increase in turbulence intensity and Reynolds shear stress over the topography. A more significant impact was caused by modifying the incoming wind shear profile, which resulted in much higher levels of Reynolds stress and turbulence intensity downstream of the escarpment. This highlights the importance of fully understanding the incoming wind profile with respect to neutral vs. non-neutral atmospheric stability conditions.

Completely different flow behaviour was observed when the escarpment leading edge was sharpened, as shown by both the POD results and in profiles of turbulent statistics. These cases showed a much larger separation bubble, much longer reattachment lengths, and vastly different distributions of shear stress and turbulence intensity as well as TKE.
production and dissipation. The normalized magnitude of turbulent properties were found to increase substantially due to the sharp edge of the escarpment, which also shifted the locations of turbulent property peaks away from the surface. This trend continued to grow with the downstream distance. Furthermore, based on comparisons to literature, the sharp edge cases showed strong similarity to the canonical case of flow over a forward-facing step, unlike the round edge cases. The results in the present study demonstrated that specific features in complex topographic terrains could have a significant impact on the associated turbulent flow field. Hence, physical modelling of the wind flow behaviour using scaled models need careful attention in accurately resolving the spatial scales of active topographic features to properly characterize the flow.
References


Chapter 4

4 Concluding remarks

This work was undertaken to investigate the influence of varying inflow conditions and model geometries on the flow over complex topography. In this chapter a summary of the experimental work completed and the main findings are provided, along with scientific contributions of the present work and its significance to the research area, and suggestions for future work.

4.1 Summary and conclusions

The objectives of this study were two-fold:

- To investigate the influence of scaling and inflow conditions on the mean and turbulent flow behaviour over a complex topography
- To investigate the underlying processes associated with this behaviour with respect to the turbulent flow characteristics

The topography of the steep Bolund hill escarpment was chosen for this study given its emergence in the wind energy community as a test case for the validation of numerical models simulating the flow in complex terrains, as well as the confirmation of physical modeling work in the laboratory setup against the full-scale field data. Experiments were conducted at two scales: 1:100 scale at the Boundary-layer Wind Tunnel Laboratory and 1:25 scale in the WindEEE dome, both at Western University. Experimental techniques included Particle Image Velocimetry (PIV) and Cobra Probe measurements. All measurements were conducted along the 270° wind direction. Overall 11 different configurations were examined with unique combinations of inflow parameters and model geometry, covering a Reynolds number range $3.6 \times 10^4 < Re < 5.2 \times 10^5$.

The results were analyzed primarily in the form of mean flow speed-up and various turbulent properties including Reynolds shear stress, turbulence intensity, and turbulent kinetic energy (TKE) production and dissipation rates, at various locations above the hill. A deep insight into the turbulent flow structure was obtained by using the Proper
Orthogonal Decomposition (POD) technique that decomposes the turbulent velocity field into its orthogonal modes.

As part of the first objective, the effect of changes to the inflow parameters including Reynolds number, upstream roughness and shape of the inflow shear profile on the flow above the escarpment were investigated. Separate conclusions are presented here for the mean flow and the turbulent flow behaviour. From mean flow perspective:

- Little to no Reynolds number dependence in the mean flow was observed at either scale, across the entire range of Reynolds numbers studied.
- Good matching of the speed-up over the escarpment was generally achieved compared to full scale results and to the results of other physical models.
- Upstream roughness had a small but repeatable effect, whereby a lower upstream roughness caused slightly higher speed-up over the hill.
- The modified shear profile had a moderate effect on the flow, causing slightly higher speed-up in the immediate vicinity of the escarpment, but lower speed-up downstream.
- Through the aid of a large model and high-resolution cameras, a small but consistent region of reverse flow was detected in the mean flow field immediately downstream of the escarpment leading edge, indicating the presence of flow separation and a recirculation bubble.
- Some discrepancies were noted between Cobra probe measurements of mean wind speeds near the hill surface for the large-scale model compared to the small-scale model. This appears more likely to be a result of model and measurement resolution than a Reynolds number dependence and should be investigated further.
In terms of the turbulent flow:

- TKE increment was observed to be generally Reynolds number independent, except for a possible weak dependence within the highly turbulent shear layer close to the hill surface, requiring further investigation to confirm.

- Upstream roughness had a moderate effect on TKE, where higher TKE increment was observed along the hill for cases with lower roughness.

- The modified shear layer profile had the effect of significantly increasing TKE and Reynolds shear stress. TKE measurements under this configuration matched much more closely to the full scale measurements above the hill surface.

The effect of modifying the escarpment leading edge was highly significant, resulting in completely different mean and turbulent flow regimes. A much larger separation bubble and longer reattachment length was observed for the sharp edge cases. Furthermore, all of the turbulent characteristics for the sharp edge configuration, including the coherent structures analyzed through POD, resembled much more closely the flow over the canonical case of a forward-facing step than the original round edge geometry.

The conclusions presented above provide insights into some of the factors that affect flow behaviour over complex topography, and their relative significance. The overall takeaway that emerges from this work is that inflow parameters and model resolution, particularly fine features of the model geometry must be carefully accounted for when modeling the flow across complex terrains. Even small changes to these parameters can cause significant and unexpected changes to the local wind regime, with possible detrimental effects on wind turbines, buildings or other infrastructure located nearby.
4.2 Contributions

The original contributions of this work to the scientific knowledge in the related field are as follows:

- Highest Reynolds number \((5.2 \times 10^5)\) and largest scale \((1:25)\) testing recorded for the Bolund topography.

- First detailed analysis of coherent structures in the flow over the Bolund topography using the proper orthogonal decomposition technique.

- Highest resolution PIV analysis for the Bolund topography.

- Tested a unique non-classical boundary layer flow over topography.

4.3 Future recommendations

Several recommendations for future work in the area of flows over complex topography are presented as follows:

- Further investigation of the Bolund escarpment is warranted, given its significance as a test case for numerical modellers, and the attention it has received from the research community. An analysis of three-dimensional effects, by means of cross-plane or stereoscopic PIV, would provide additional insights into the flow behaviour.

- A comparison of wind tunnel results could be made to the most recently available LIDAR field measurements, to better understand the similarities and discrepancies of the wind tunnel flows to the full-scale flow at locations apart from the limited number of mast positions.

- The leeward side of the escarpment could be investigated at high resolution. Trailing edge dynamics including vortex shedding could be compared to those of elongated bluff bodies.

- A dedicated study of separation bubble dynamics for escarpment flows could be undertaken, whereby the influence of parameters such as surface roughness,
inflow turbulence intensity and leading edge curvature on the dimensions of the bubble reattachment length and turbulent characteristics are investigated.

- Identical topographies could be tested at different scales in the same facility under identical inflow conditions, to truly isolate the effects of geometric scaling.
- Finally, the impact of the escarpment topography on wind energy applications could be investigated through the integration of scale model wind turbines on the Bolund hill model and detailed flow characterization around the wind turbines.
Appendix A: PIV error calculation

The total error in Particle Image Velocimetry can be calculated by adding all the errors caused from different sources. These error sources are particle diameter, seeding density, out of plane motion, velocity gradient, dynamic range, peak locking and Adaptive Gaussian Window interpolation [1]. The errors from different sources were calculated based on Figs. 5(a-f) provided by Cowen and Monismith [1]. Accordingly, the total error is the sum of mean and RMS errors of the above error sources. They referred to the random uncertainty in locating both the correlation peak and particle image as RMS error. This type of error is caused by random noise during imaging process.

The particle diameter from the fog generator is estimated to be 5μm, based on the estimate by Ayotte and Hughes for a similar machine [2], thus the tracer particle has a diameter of 0.026 pixels. Fig. 5(a) in Cowen and Monismith [1] provides the error due to particle diameter. Since the smallest particle diameter in the figure is 1 pixel, the error due to particle size was calculated based on this diameter and is equal to

\[ \varepsilon_u = (-0.03) + 0.095 = 0.065 \text{ pixels} \quad (1) \]

Fig. 13 in Prasad et al. [3] which shows the bias and peak locking errors as a function of particle diameter was used as an approximation for estimating the error corresponding to a particle diameter of 0.355 pixels. The figure shows that the error associated with a particle diameter of 0.355 pixels is larger by 40% compared to the error associated with a particle diameter of 1 pixel. In the study of Prasad et al. [3], the centre of mass cross-correlation procedure is susceptible to peak locking. On the other hand, the current work used three point Gaussian estimation which has a reduced peak locking error. Thus, additional error in particle diameter was estimated to be 30%. The final error estimation for particle diameter is

\[ \varepsilon_u = 0.065 \times 1.3 = 0.0845 \text{ pixels} \quad (2) \]

PIV error was calculated based on the largest average velocity gradient across all directions in all measurement planes. The largest average velocity gradient was for the
U15RC1 case, where $\frac{\partial u}{\partial y} = 114$ s$^{-1}$. With spatial resolution of 0.01902 cm/px and $\Delta t$ of 150 $\mu$s, this is equivalent to 0.017 px/px. Thus, the error estimation will be conducted using that velocity gradient. The error due to velocity gradients was estimated based on Fig. 5(e) in Cowen and Monismith [1]. The total error due to velocity gradient is the sum of both mean and RMS errors which is equal to

$$\varepsilon_u = (-0.02) + 0.06 = 0.04 \text{ pixels} \quad (3)$$

Thus the total error from the velocity gradient and particle diameter is

$$\varepsilon_u = 0.04 + 0.0845 = 0.1245 \text{ pixels} \quad (4)$$

To estimate the error due to out of plane motion, the displacement in the traverse direction was calculated. First, based on the results obtained in the cross plane, the velocities in the vertical and span-wise direction are comparable. Thus, it is safe to assume that the displacement in the out of plane motion (i.e. span-wise direction) is equal to the displacement in the vertical direction and equals to summing the mean and standard deviation of the vertical displacement

$$\Delta z = \Delta \bar{z} + \sigma_z = 1.74 \text{ pixels} \quad (5)$$

For the vertical plane, 1.74 pixels equals to 0.33 mm. Since the laser sheet thickness is 3 mm, this out of plane displacement can be neglected. Fig. 5f in [1] was used to calculate the error associated with Adaptive Gaussian Window (AGW) interpolation. This figure shows AGW averaging error as a function of dynamic range. For 8-bit CCD cameras, the dynamic range varies between 100 and 150 counts. Therefore, the AGW averaging error is approximated to be 0.08 pixels and total error is

$$\varepsilon_u = 0.1245 + 0.08 = 0.2045 \text{ pixels} \quad (6)$$

Therefore, the total error of measurement is 0.26 m/s, or 1.7% as a percentage of incoming wind speed at hill height.
References


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