

## FLOW OVER A STEEP ROUGH HILL

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**Abstract.** *This paper presents the study of the effects that a steep topographical elevation exerts on the properties of a neutrally stratified, fully rough turbulent boundary layer. The main concern of the present work is to experimentally investigate the influence of surface roughness on the behaviour of the mean and turbulent velocity fields along the topography. Laser-Doppler anemometry was used to measure the longitudinal and vertical mean velocities and its fluctuation components, in a water-channel environment. Original and detailed measurements of the recirculation region downstream of the crest are presented.*

**keywords:** *Flow over hills, Roughness, Separation, Laser-Doppler anemometry, Turbulence.*

### 1. Introduction

In micrometeorology, the mathematical description of the flow field over an arbitrary terrain is always a difficult exercise. In fact, the natural non-uniformities resulting from changes in the land surface pose many problems that are of difficult modelling and solution.

In the past, owing to its simplicity, most of the systematic investigations on the surface layer and on its overlying boundary layer were confined to the simplest topography, the boundary layer over a flat, open land. Studies involving more complex situations such as flows over flat but heterogeneous surfaces or over hills were then just a few. The causes for the scarcity in analyses were clear. From the mathematical standpoint, atmospheric fluid motion is governed by a set of non-linear, second order, partial differential equations, and that renders the development of practical useful solutions a very difficult affair. On the other hand, on the experimental front, the difficulties in conducting field measurements frequently result on logistical requirements of an unsurpassable nature.

For low hills, with a gentle slope and an idealised shape, the equations of motion can be linearized to furnish simple analytical solutions that can be used to find mean wind velocity changes near the surface and rudimentary predictions of the flow turbulence structure. However, for large, steep hills the occurrence of flow separation and the formation of a large scale recirculating flow region adds much complexity to the problem. In fact, when hills become steep enough to form large downstream separation regions, many of the classical theories based on perturbation techniques break down. The pressure field cannot be simply approximated by the potential flow around the hill, but must be calculated considering the hill shape and the separation region. Thus, when separation occurs, not only the flow in the separation region changes, but significant changes occur in the whole flow field over the hill.

Moreover, the characteristics of the recirculation region, as well as the position of the separation and reattachment points are deeply dependent on the properties of the surface roughness. As a consequence, quantifying

the separated flow and the surface roughness parameter is a necessary and fundamental step for a faithful characterization of the velocity field.

The purpose of this work is to study the flow over hills which are steep enough so that large separation regions are formed on its downstream side. Our main concern is to experimentally investigate the influence of the surface roughness on the behaviour of the mean and turbulent velocity fields over the elevation. In particular, our interest is to study the characteristics of the flow inside and in the neighbourhood of the recirculation region that is formed on the lee side of the hill. A neutrally stratified, fully rough boundary layer flowing over a steep model hill has been simulated in a water channel environment. The rough surface used in the present work was essentially two-dimensional. It was comprised by a sequence of square bars equally distributed over the smooth wall of the water channel. The two-dimensional hill was constructed with a Witch of Agnesi shape with a maximum  $18.6^\circ$  slope. Measurements of longitudinal and vertical components of mean velocity and its turbulent components were carried out with the aid of laser Doppler anemometry. The present results allow a thorough description of the near-wall flow, extending from the upstream region, along into the separated zone to the downstream lee side.

As a consequence of the presence of the recirculation region, the prediction of turbulent flow over a steep hill naturally lends itself to the use of non-linear models. That has, indeed, been the general trend over the last 10 years. The natural increase in computer power, together with the development of a host of turbulence models, has witnessed a large increase on the number of non-linear numerical simulations of atmospheric flows. Typical numerical simulations included two-equation eddy-viscosity turbulence models, algebraic Reynolds stress models, second-order closure models and large eddy simulation. All simulations, however, irrespective of the type of closure scheme chosen, suffer with the specification of the boundary conditions at the wall.

From this perspective, the main contribution of the present manuscript is to provide detailed and refined experimental data on neutrally stratified flows over a steep rough hill, in particular inside the recirculation region. These data are representative of a typical problem which commonly occurs in nature and technology. In fact, this work constitutes a further step in extending the problem to more complex situations. A previous and more fundamental step, which considered solely the effects of a smooth steep hill on the properties of a turbulent boundary layer has been made by Loureiro et al. (2006). Indeed, it is crucial to have a well-established knowledge of the main mechanisms involved on the separation behind smooth hill crests before proceeding to study additional features such as the roughness effects. Our aim is now to consider only the effects of hill roughness, shape and slope. Other contributions such as stratification effects are not in the scope of this work.

## **2. A brief literature review**

Many theoretical and experimental studies have been carried out to analyse the effects that two and three-dimensional hills cause on the mean velocity and turbulence fields of the atmospheric boundary layer. In the following, we present some representative work of previous contributions. This short review, we expect, will provide the reader with a good idea on the state of the art for the experimental representation of the flow over hills.

Without any doubt, the works that have had a most profound influence on the way one thinks about the problem are the works of Hunt and his co-workers. These works have resorted to asymptotic methods to describe the flow over low hills, where the equations of motion can be linearized. Hunt has suggested the existence of a flow structure equivalent to the classical two-layered model developed for the aerodynamic boundary layer. In the inner layer, the flow is expected to be in equilibrium with the current boundary conditions so that its structure can be predicted on the basis of the wall laws. In the outer layer, turbulence is expected to be modified according to the rapid distortion theory of Townsend (1972).

In a seminal work, Jackson and Hunt (1975) showed that, for a low hill of rough surface, the eddy viscosity distribution for equilibrium flow near a wall can still be used to determine the changes in Reynolds stress. The theory also showed that for a log-profile upwind the increase in wind speed near the surface of the hill is  $O((H/L)U_o(L))$  where  $H$  and  $L$  are respectively the characteristic height and length of the hill and  $U_o(L)$  is the velocity of incidence wind at  $L$ . The conclusion was that the increase in surface winds can be considerably greater than that furnished by potential flow theory. Another conclusion was that at the point above the top of the hill where velocity reaches its maximum value, the velocity is approximately equal to the velocity at the same elevation above ground level upwind of the hill. The surface stress was found to be very sensitive to changes in elevation, being doubled by a hill with slope as small as one in five.

Britter et al. (1981) studied an air flow over a two-dimensional hill. The emphasis was on characterizing the velocity speed up, the surface roughness effects and the properties of turbulence. The hill was two-dimensional, bell shaped, with a maximum slope 0.26. Mean and fluctuating longitudinal velocities were measured with a constant temperature anemometer and a pulsed wire anemometer. The mean velocity profiles were compared with predictions given by the two-layered model of Jackson and Hunt(1975) furnishing close agreement for locations upwind of the hill top but not in the separated flow region. In a second experiment, flow over a

smooth hill with a rough surface was studied. The authors showed that, for this geometry, flow speed up can be evaluated by a linear superposition of effects provoked by the changes in elevation and in roughness. In the lee of the hill, however, the roughness completely changed the flow configuration suppressing separation and the linear superposition effect.

The structure of strongly stratified flow over three-dimensional hills was discussed by Snyder et al. (1985) both from a theoretical and experimental point of view. The paper discusses extensively the dividing streamline concept, taking as a basis for the analysis Sheppard's energy arguments for an estimation of the height of this dividing streamline. The authors analyse an extensive range of laboratory observations and measurements of stratified flows over a range of hills with different geometries subjected to different oncoming flows.

Concerned with the effects that hills provoke on turbulence, Zeman and Jensen (1987) developed a new model where the von Mises transformation was applied to the mean momentum equations and the second-order closure type turbulence equations were solved. All predictions were compared with data from the Askervien Hill project.

At around the same time, Snyder and Britter (1987) carried out an experimental research very similar to Arya and Gadiyaram(1986), triangular and bell shaped hills with varying crosswind aspect ratio were studied. Velocity measurements were made with a cross-film anemometer. This fact prevented the characterization of the wake region. The separation region was observed to decrease in size with increasing aspect ratio and changes in the flow parameters were explained with the notion that the effective hill shape was formed by the hill and the resulting recirculation region.

Castro and Apsley (1997) performed computations for the flow and dispersion over two-dimensional hills of various slopes in a neutrally stable boundary layer. The results were compared with laboratory data. The authors showed that a suitably modified  $\kappa$ - $\epsilon$  model generally produced good agreement for the mean behaviour, but lower values for the turbulent kinetic energy and the lateral plume spread. Corrections in the standard  $\kappa$ - $\epsilon$  model allowed the authors to account for streamline curvature effects. For a hill with a sufficiently large slope the levels of concentration were found to be well predicted. For hills with lower slopes that provoked intermittent separation, less satisfactory results were observed.

The prospects for the application of large eddy modeling to the description of flows over hills were analyzed by Wood (2000). After recognizing the remarkable progresses that have been achieved through linear theories, the author emphasizes the urgent need for the development of a computationally cheap method for the prediction of mean and turbulent flow in the lee of steep hills for which non-linear processes dominate. The author further reminds us that the dynamics and the structure of separation and turbulent wakes are still poorly understood. In this scenario, it is argued that large-eddy simulations seem to be a well suited technique for the numerical investigation of flow in complex terrain.

A wind tunnel study of turbulent flow over a 3-D steep hill was performed by Simpson et al. (2002). Through three -velocity component laser Doppler velocimeter measurements, the complex vortical separations that occur on the lee of the hill were characterized in a plane downstream of the hill. The authors conclude that only two large streamwise vortices are formed, one on each side of the centerline.

Two dimensional steep hills in both neutral and stably stratified flow conditions were also studied by Ross et al.(2004). Turbulence models that used one-and-a-half and second-order closure schemes were used to predict the mean and turbulent quantities of the flow. The numerical predictions were compared to new wind tunnel experiments carried out for two hills with different slopes, one of which was steep enough to cause flow separation. The data, obtained through laser Doppler anemometry included mean and turbulent properties of the flow. The wall flow region was treated accordingly to the procedure of Ying and Canuto (1997). The authors report a reasonable prediction for mean flow characteristics for all flow conditions. However, large differences are observed in the separated flow region in the lee side of the hill.

The ability of non-linear eddy-viscosity and second-moment models to describe the flow over two- and three-dimensional hills was investigated by Wang et al. (2004). Five turbulence models were analyzed: two cubic eddy-viscosity models, an explicit algebraic Reynolds-stress model, a quadratic eddy-viscosity model and a Reynolds-stress-transport model. The one major objective of the paper was to examine the flow separation patterns that occur on the lee side of 2D- and 3D-hills. The authors report that in 2D-flow the predicted separation differs greatly from one model to the other, with just one non-linear model performing well. In 3D-flow, none of the models were found to give a good representation of the complex multi-vortical separation pattern.

### **3. Experimental apparatus**

The rapid development of the aeronautical industry during the sixties has established wind tunnels as the most appropriate and low-cost facility to simulate natural flow conditions. In the past, though, several investigators have resorted to water experimentation in order to examine the flow over hills and other obstacles.

Long (1959), Snyder (1985) and more recently by Gyüre and János (2003) are quite clear examples of the use of the towing tank method. Indeed, towing tanks are quite appropriate when considering atmospheric flows dominated by blocking, lee waves, inversions and strong stratification effects. However, as explained by Meroney (1990), the towing tank method may distort surface layer predictions because the uniform approach profile simulated is not equivalent to shear flow found near the earth’s surface. Water-channel experiments, on the other hand, do not suffer from this weakness. The mean and turbulent boundary layer profile can be accurately reproduced in this facility. The ratios of longitudinal and vertical fluctuation components of the simulated inner layer are comparable to atmospheric data, as presented in the results section.

### 3.1. Water channel

The present experiments were conducted at the Hydraulics Laboratory (FEUP). The problem under study has been simulated in a 17 m long water channel, with cross sectional area of 0.60 m high per 0.40 m wide. The side walls of the channel were made of glass, so as to make it convenient to perform any visual inspection of the flow, as well as to permit an appropriate use of the laser-Doppler anemometer.

The water recirculation system consists of two underground tanks, four pumps with a maximum capacity of 150 l/s and one upper stabilizing tank. The working section was 3 m long, and was situated 10.3 m downstream of the channel entrance. The model of the hill was located 12 m from the channel entrance.

During a typical run, two pumps sufficed to be used to keep the system running in a steady state, with a maximum flow rate variation of  $\pm 0.8\%$ . At the entrance of the channel, the water was made to pass through a series of screens and filters so as to stabilize, make uniform and suppress any excessive level of turbulence. The screens and filters were also used to control the grain-size of the particles in suspension in the water. To guarantee a flow rate control of 0.001 l/s, a magnetic flowmeter was installed in the supply line. The water depth along the channel was controlled by a vertical steel gate. For the present measurements a flow rate of 26.7 l/s and water height of 267.5 mm were employed during the whole experimental campaign. An illustration of the water channel is shown in Figure (1.a), and the hill is shown in Figure (1.b).

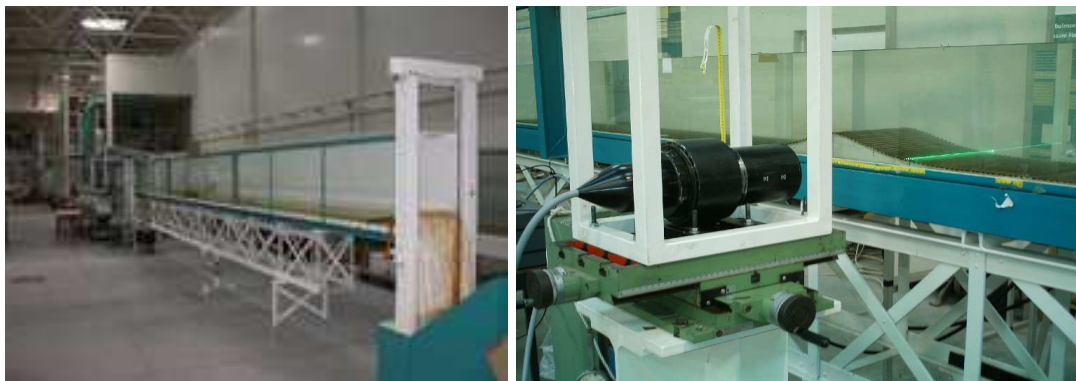


Figure 1: Illustration of the water channel and model hill.

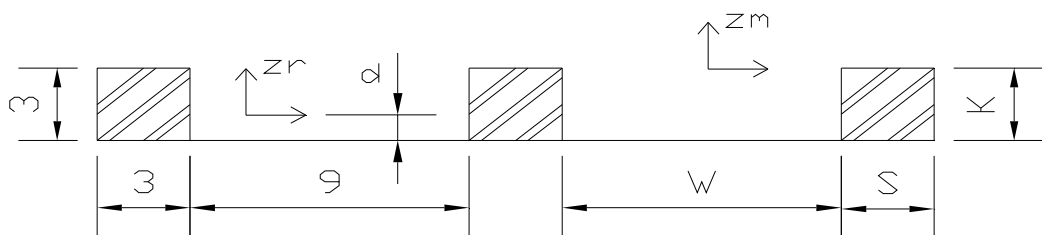


Figure 2: Geometrical details of the simulated rough surface. Dimensions in mm.

### 3.2. Characteristics of the hill and rough surface

For the present work, the same model used in the work of Loureiro et al. (2005) has been used. Following the geometrical characteristics used by Loureiro et al. (2000, 2001), the shape of the hill was given by a modified “Witch of Agnesi” profile, according to the equation

$$z_H = H_1[1 + (x/L_H)^2]^{-1} - H_2. \quad (1)$$

Thus, it follows that  $H (=H_1 - H_2)$  ( $= 60$  mm) is the hill height and  $L_H$  ( $= 150$  mm) is the characteristic length of the hill representing the distance from the crest to the half-height point. Co-ordinates  $x$  and  $z$  represent the longitudinal and the vertical axes, respectively. This curve has been extensively used in literature, e. g. Britter and Hunt (1981) and Arya et al. (1987).

The rough surface was simulated through the use of rubber strips of 3 mm per 3 mm cross section spaced by 9 mm gaps. These bars have been regularly distributed along the test section. The rough surface extended from 1.5 m upstream of the hill top until 1.5 m downstream. The geometrical details of the simulated surface are given in Figure (2). Please note that measurements have been carried out considering the top of the roughness elements as the origin of the vertical profiles, as illustrated in Fig. (2). However, the actual origin of the velocity profile is located somewhere between the flat floor and the height of the roughnesses elements. This shift in origin is usually called the displacement height  $d$ , which be explained further in the manuscript.

### 3.3. Instrumentation

A two-component Dantec laser-Doppler anemometry system was used in the forward scatter mode to conduct the measurements of the mean and fluctuating velocity field. A Bragg cell unit was used to introduce a total optical-electronic shift of 0.6 MHz, allowing the resolution of the direction of the flow field and the correct measurement of near-zero mean velocities. The beams were made to pass through a series of conditioning optical elements, in order to achieve a small measurement volume and to improve the optical alignment. Front lenses of 500 mm focus length were mounted on the probe in order to accurately position the measurement volume on the centerline of the water channel. Before being collected by the photomultiplier, the scattered light was made to pass through an interference filter of 514.5 nm, so that only the green light is acquired. The same procedure was carried out to acquire the blue light, with a filter of 488nm. The signal from the photomultiplier was band-pass filtered and processed by a Burst Spectrum Analyzer, operating in the single measurement per burst mode. A series of LDA biases were avoided by adjusting the strictest parameters on the data processor. For this set of experiments, a level validation of 8 and a signal to noise ratio of 5 was chosen. For the simultaneous measurements of longitudinal and the vertical velocities, a coincidence window of 5000  $\mu$ s was used. For each point measured, a sample size of 20,000 values has been considered. Table (1) lists the main characteristics of the laser-Doppler system used.

Table 1: Main characteristics of the laser-Doppler system.

Wavelength	514.5 nm (green) 488nm (blue)
Half-angle between beams	1.604°
Fringe spacing	9.191 $\mu$ m (green) 8.718 $\mu$ m (blue)
Beam spacing	28 mm
Beam diameter	2.2 mm
Dimensions of the measurement volume	
Major axis	5.31 mm (green) 5.04 mm (blue)
Minor axis	149.0 $\mu$ m (green) 141.0 $\mu$ m (blue)

This whole system was used to measure both the longitudinal and the vertical velocity components. Typical uncertainties associated to the mean velocity data,  $U$ ,  $W$ , are lower than 0.2% of the free stream velocity,  $u_\delta$ . Further downstream of the hilltop, in high level turbulence regions, these maximum uncertainties increase to about 0.3% of the free stream velocity. As for the Reynolds stress components  $u'u'$ ,  $w'w'$ ,  $u'w'$ , uncertainties were estimated in 2.3%, 1.8%, 4.2% of the friction velocity in the undisturbed flow (for the Reynolds shear stress the uncertainty is given in percentage of the square of the friction velocity of the undisturbed flow), respectively, increasing to 3.8%, 3.5% and 6.9% in regions of high turbulence.

## 4. Results

Firstly, the properties of the undisturbed boundary layer are shown and discussed. Then, the results for the perturbed flow field over the hill are presented. For clarity, and to identify which mechanisms are dominant in each region, the results will be particularly split into three blocks: data for the flow field upstream of the top of the hill, data for the recirculation region and data for the returning to equilibrium region. Hereafter, all the data are shown in reference to a Cartesian coordinate system located at the symmetrical axis of the hill. All the profiles were measured at the centerline of the water-channel. Measurements were taken at 11 stations along the test section, and Figure (3) illustrates its spatial distribution.

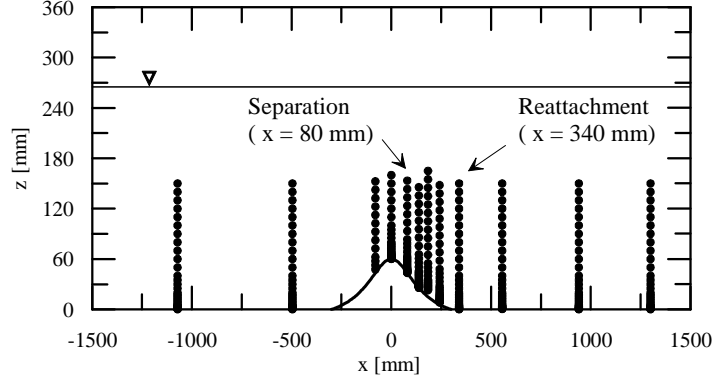


Figure 3: Spatial distribution of the measured profiles and illustration of the coordinate system.

### 4.1. Undisturbed Boundary Layer

The characterisation of the undisturbed flow will provide reference data for the evaluation of the perturbed flow field over the hill. For the present experiment, the reference mean and turbulent velocity profiles were measured at station  $x = -1072$  mm. Figure (4.a) shows the longitudinal mean profile in normalised physical coordinates, where  $\delta$  denotes the boundary layer thickness and  $U_\delta$  the free stream velocity. The streamwise fluctuation profile measured in the undisturbed station is shown in Figure (4.b). Measurements assure that the oncoming boundary layer was fully developed and followed approximately the  $(z/\delta)^{1/7}$  power law behaviour.

For a rough surface, the law of wall can be written as:

$$U = \frac{u_\tau}{\varkappa} \ln \left( \frac{z-d}{z_0} \right), \quad (2)$$

where  $\varkappa$  is the von Karman constant,  $d$  is the displacement height and  $z_0$  is the roughness length. Eq. (2) is, in engineering and meteorological literature, a customary way to write the logarithmic law for the velocity profile over rough surfaces, e. g. Perry and Joubert (1963), Jackson (1981), Malhi (1996).

In order to evaluate the friction velocity for the undisturbed boundary layer over rough surface, the Reynolds shear stress profile was used. Assuming that at some distance from the wall the turbulent stresses are the dominant part of the total shear stresses, a region of constant distribution can be identified in the  $-\overline{u'w'}$  profile. The mean value of  $-\overline{u'w'}$  in this region can then be used to calculate  $u_\tau$ . The value of the friction velocity was calculated as  $u_\tau = 0.072 U_\delta$ . This value is in 5% agreement with the data of Britter et al. (1981),  $u_\tau = 0.0685 U_\delta$ , and Athanassiadou and Castro (2001),  $u_\tau = 0.06 U_\delta$ .

Once the friction velocity is known, the roughness related parameters  $d$  and  $z_0$  can be found through Eq. (2). According to Malhi (1996), the displacement height  $d$  is mainly a dynamic quantity, and is related to the behaviour of the transport mechanisms. On the other hand, the roughness length  $z_0$  is considered as uniquely related to the geometry of the underlying surface and is independent of meteorological variables. Using the graphical method of Perry and Joubert(1963), the velocity profile was plotted in a log-linear graph in dimensional coordinates, Fig. (4.c). Then, the normal distance from the flat surface (bottom of the roughness elements) was decremented in steps of 0.1 mm and a straight fit was applied to the logarithmic region. The angular coefficient of this fit was kept constant through the specification of  $u_\tau$  previously calculated from  $-\overline{u'w'}$  profile. The most appropriate curve was chosen by searching for the maximum coefficient of determination, R-squared, thus providing us with the best value for  $d$ . Others statistical parameters were also considered in

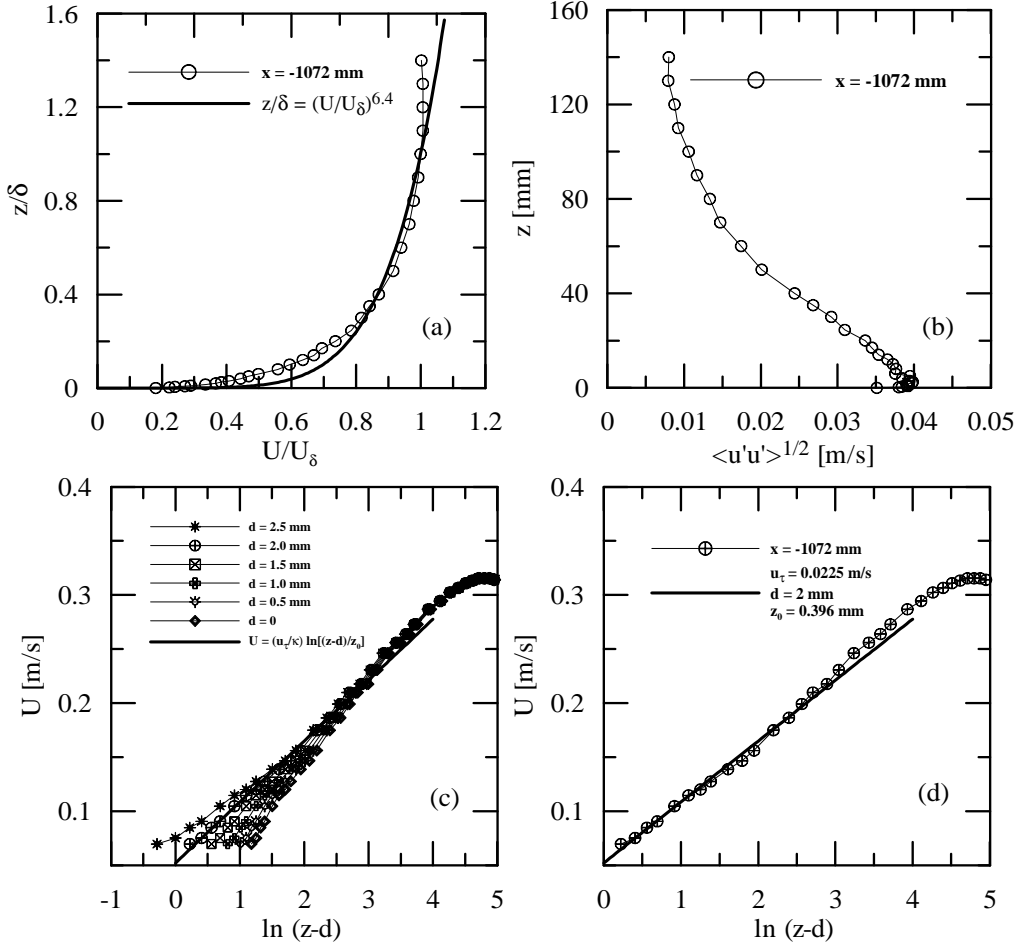


Figure 4: Undisturbed streamwise flow. (a) Mean velocity profile, (b) Turbulent velocity profile, (c) Estimation of  $d$  and  $z_0$  (d) Logarithmic velocity profile.

this evaluation process. The determination of the error in origin for the velocity boundary layer is illustrated in Figure (4.c). Consequently, according to Eq. (2), the value of  $z_0$  is calculated from the linear coefficient of the most appropriate curve fit.

The selected curve fit is illustrated in Fig. (4.d). The global and local properties of the undisturbed boundary layer are presented in Table (2).

Table 2: Properties of undisturbed profile.

Boundary layer thickness	$\delta$	100 mm
External velocity	$U_\delta$	0.3133 m/s
Friction velocity	$u_*$	0.022537 m/s
Roughness length	$z_0$	0.396 mm
Reynolds roughness length	$U_\delta z_0 / \nu$	123

Longitudinal mean velocity profiles are presented in Figure (5). Please note the argument  $(z - z_H)$  shifts the origin of the coordinate system from the flat surface to the hill surface, see Eq. (1) and Fig (3). Measurements performed upstream of the hill top are shown in Fig. (5.a). The region of accelerated flow upwind to the crest can be clearly noted.

The profiles along the separation region are introduced in Fig (5.b), where the reversed near-wall flow region is fairly well characterised. The separation point was observed to occur approximately at  $x = 80$  mm, and reattachment was observed at around  $x = 400$  mm. Fig (5.c) presents the velocity profiles downstream of the

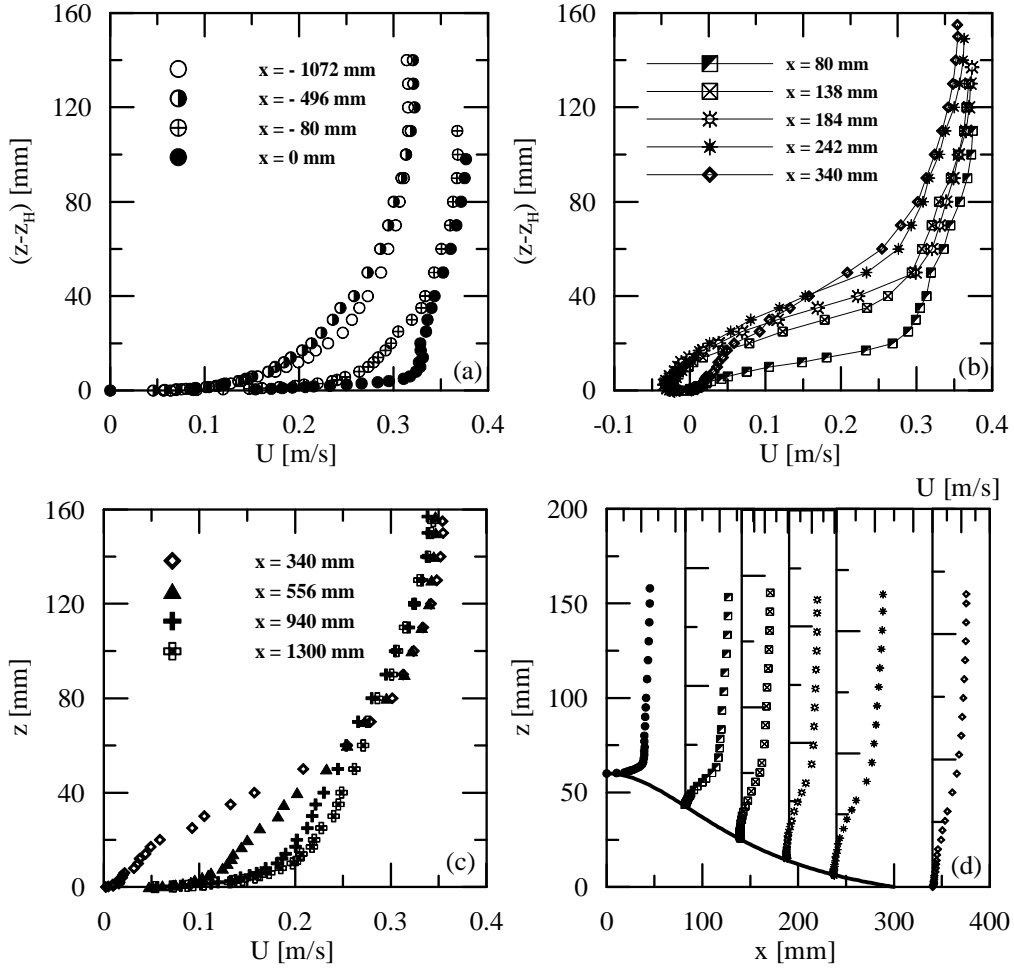


Figure 5: Mean longitudinal velocity at the 11 measured stations.

wake, where the boundary layer is returning to its equilibrium conditions. An overview of the recirculation is shown in the Fig (5.d).

The changes in the longitudinal fluctuating velocity profiles are shown in Fig. (6). In the accelerated flow region upstream of the hill (Fig. 6.a),  $\overline{u'u'}$  is observed to increase slightly along the upwind slope ( $x/H = -2.5$ ), until the crest is reached. At the hill top,  $\overline{u'u'}$  is about 2.5% its undisturbed value in the near-wall region.

In the separated flow region (Fig. 6.b), the peak value for  $\overline{u'u'}$  increases by 75% as compared with its undisturbed profile. In addition, the large increase in peak values for  $\overline{u'u'}$ , as well as its increasing distancing from the wall toward the shear layer results from the turbulence production term  $P_{uu} = -2\overline{u'w'}(\partial U/\partial z)$ . The maximum peak value for  $\overline{u'u'}$  is located at  $x = 340$  mm, approximately the reattachment point,  $z = 30$  mm. Downstream of the hill (Fig. 6.c), at stations  $x = 940$  mm and 1300 mm, the  $\overline{u'u'}$  profiles can still be distinguished from each other and from the undisturbed profile.

In general, in this region, turbulence profiles are characterized by an elevated maximum whose distance to the wall increases with increasing distance from the hill.

The behaviour of  $-\overline{u'w'}$  is presented in Fig. (7). On the upwind side of the hill the changes in the Reynolds shear stress profiles are relatively small and vary slowly with height (Fig. 7.a). Notable changes in  $-\overline{u'w'}$  are observed just as the flow passes the hill top. Then, a large increase in  $-\overline{u'w'}$  is observed, of the order of five times. This behavior can be explained by the enhanced shear effects through the production term  $P_{u'w'} = 2\overline{w'^2}(\partial U/\partial z)$ . Similar to the peak locations for  $\overline{u'u'}$ , the highest value of  $-\overline{u'w'}$  is found at position  $x = 380$ ,  $z = 40$  mm. No inner region of constant  $-\overline{u'w'}$  was noted in the separated flow region. Downstream of the hill, at stations  $x = 556$  and 940,  $-\overline{u'w'}$  shows a nearly constant near wall region, but the difference in  $-\overline{u'w'}$  between these stations is around a factor of two.



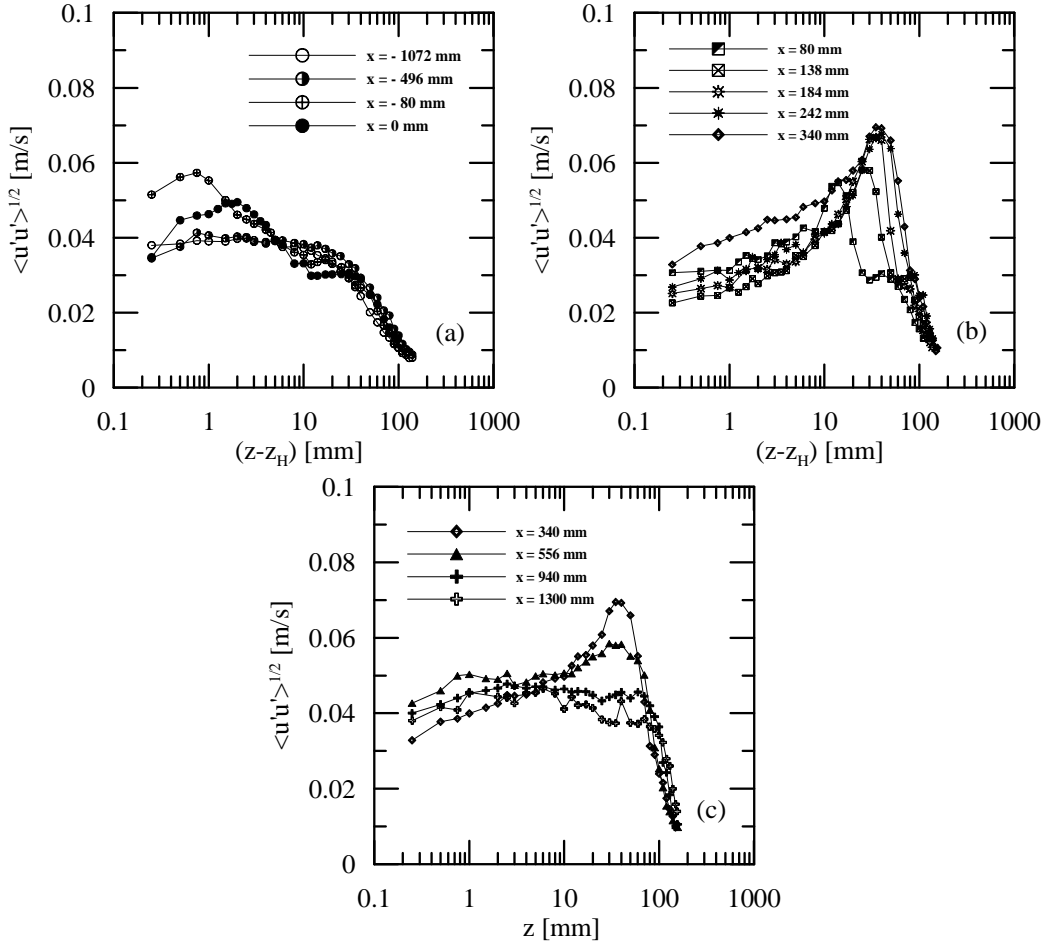


Figure 6: Streamwise turbulent velocity profiles measured along the hill.

## 5. Final remarks

This work has experimentally investigated the influence of the surface roughness on the behaviour of the mean and turbulent velocity fields along a steep hill. Particular attention was dedicated to the study of the characteristics of the recirculation region. A neutrally stratified flow over a steep rough elevation has been simulated in a water channel environment. Measurements of longitudinal and vertical components of mean velocity and its fluctuation components were conducted with the aid of a two-component laser Doppler anemometry.

At the present stage, the research has striven in characterising the flow in four distinct regions: in the undisturbed region upstream of the hill, on the top of the hill, inside the and in the undisturbed region downstream of the hill. The present results allow a thorough description of the inner region of the boundary layer, providing good quality near-wall data to serve as a test case for numerical simulations.

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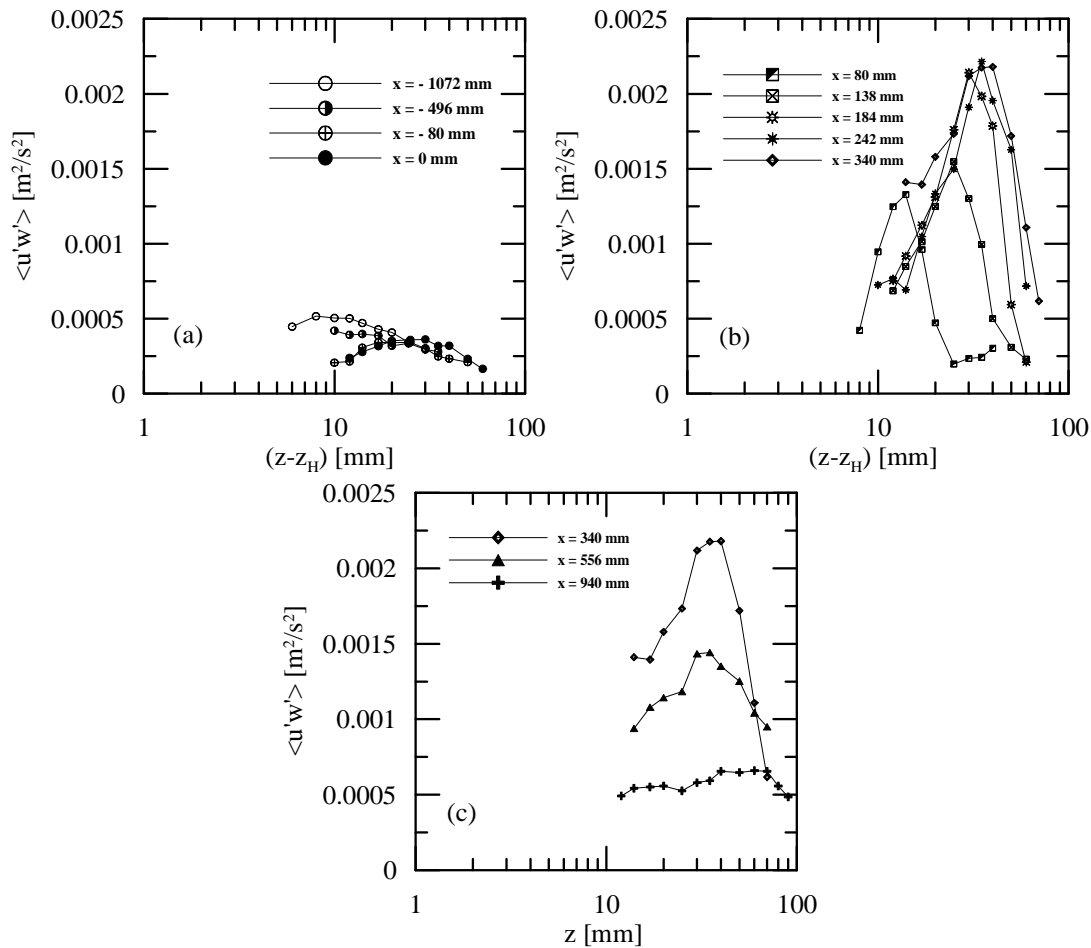


Figure 7: Reynolds stress profiles measured along the hill.

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