Influence of Integral Length Scales on Sand Erosion Techniques

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Abstract. *This paper presents results of ongoing research of the flow within an urban canopy. Hot-wire anemometry and sand erosion is used to assess the wind velocity near the ground. The results show that the incoming boundary layer, if simple, does not affect much the flow near the ground even though an appropriate scaling is needed.*

Keywords: *atmospheric boundary layer, sand erosion, wind tunnel testing, urban canopy, ground level wind*

1. Introduction

This paper presents the first results of ongoing research carried by IPT (Instituto de Pesquisas Tecnológicas do Estado de S.P.) and FAU (Faculdade de Arquitetura e Urbanismo da Universidade de São Paulo) on turbulent flows inside urban canopies. These flows are extremely complex and detailed modelling is usually difficult if not impossible unless simplifying hypothesis are assumed. This paper studies the effect of upstream boundary layer characteristics on the flow inside an urban canopy.

It has long been recognized the importance of appropriate modelling of the boundary layer (see Cook, 1985 for instance). Not only should the velocity profile be correctly modelled but turbulence characteristics are also very important. The simulation scale is usually a result of the boundary layer under simulation in the wind tunnel. The integral length scale of turbulence inside the wind tunnel should be such that

$$\frac{L^x_{\text{wind tunnel}}}{L_{\text{model}}} = \frac{L^x_{\text{atmosphere}}}{L_{\text{prototype}}}$$

where $L^x_{\text{wind tunnel}}$ is the integral length scale of the boundary layer in the wind tunnel, $L^x_{\text{atmosphere}}$ is the integral length scale of the atmosphere, L_{model} is a characteristic length of the model under testing and $L_{\text{prototype}}$ is the analogous length scale of the prototype. With these scales relationship, the modelling scale should be

$$n = \frac{L^x_{\text{wind tunnel}}}{L^x_{\text{atmosphere}}} \tag{1}$$

This approach is common in wind engineering even though it doesn't consider the influence of smaller scales or accurate turbulence spectrum. The problem is that once scales of the order of $1/500$ or smaller are needed, setting up the wind tunnel is not trivial. The objective of this paper is to determine whether the turbulence generated by obstacles inside an urban canopy are capable to overwhelming the influence of the boundary layer so that a simpler modelling approach to the boundary layer is sufficient when interest is focused in regions well within the urban canopy.

2. Experimental setup

2.1 Wind tunnel description

The tests were conducted in IPT's Atmospheric Boundary Layer Wind tunnel (TUC). This wind tunnel, in operation since June 2002 has a test section $3\ m$ wide and $2\ m$ high and it is $17\ m$ long. The maximum velocity in the wind tunnel is around $23\ m/s$.

The boundary layer was simulated using the Counihan method (Counihan 1971) so that the boundary layer is about $1,2\ m$ high.

2.2 Instrumentation

The sand erosion patterns were recorded with a digital camera. The velocity profiles were measured with a single wire hot-wire anemometer from DANTEC. Reference velocity of the wind tunnel was measured with a static Pitot tube.

2.3 Model description

Two models were built with interchangeable parts (actually wooden blocks with sizes being multiples of a base value) so that new configurations may be tested. The two models are similar but every linear dimension of the larger model is twice that of the smaller one.

In the current model, the blocks form a few canyons in the direction of the mean flow and perpendicular to it. There is also a large square approximately in the middle of the model. Figure 1 shows a photograph of top view of the smaller model taken during the sand erosion test.

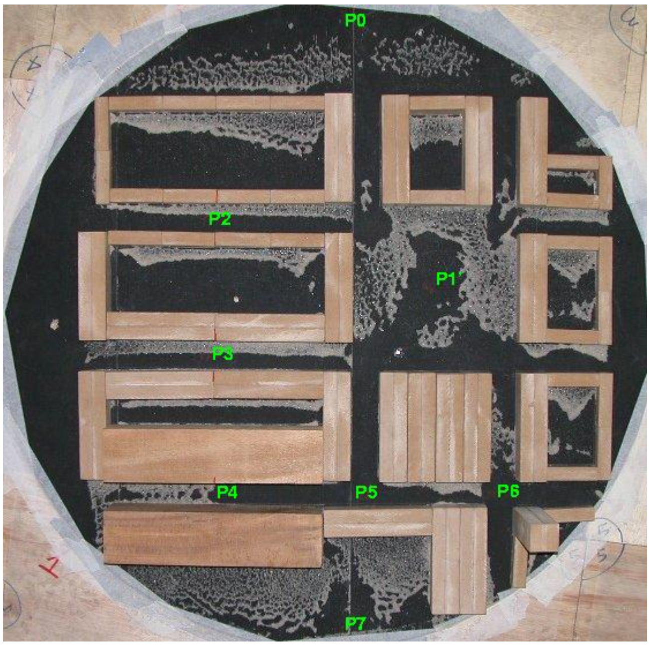

Figure 1. Top view of the model with sand erosion patterns. Also indicated are the positions where the boundary layer was measured

3. The simulated boundary layer

The boundary layer was simulated for a smooth terrain terrain with power lay exponent of $\alpha = 0,1$ and roughness length $z_0 = 0,03mm$. Figure 2 shows the mean velocity profile, turbulence intensity profile ($\sqrt{u^2}/U$) and integral length scale defined according to the following equation (Simiu and Scanlan, 1996):

$$L = \frac{1}{2\pi}\frac{\bar{U}}{n_{\text{peak}}} \tag{2}$$

In this equation $\bar{U}$ is the mean velocity and n_{peak} is the frequency where the non dimensional spectrum $\frac{nS}{u^2}$ is maximum.

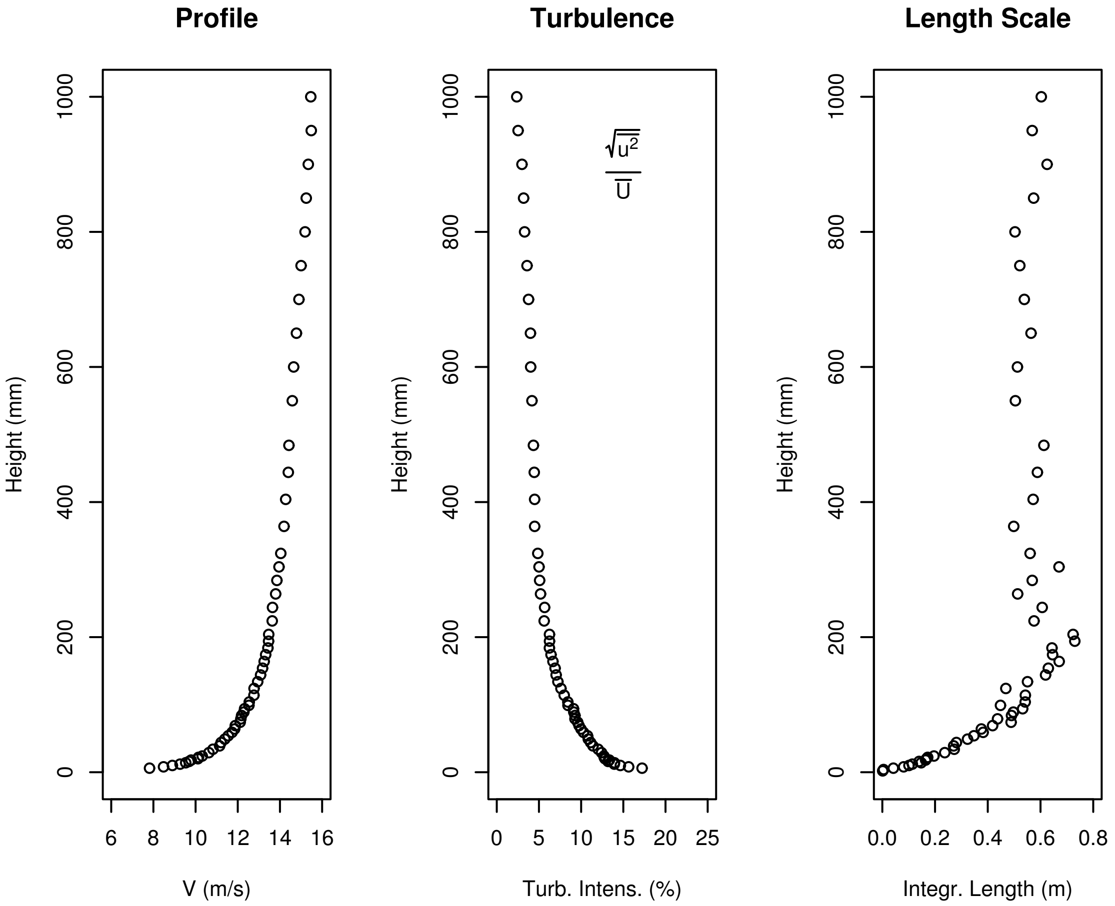

Figure 2. Velocity, turbulence intensity and integral length scales for incident boundary layer

4. Sand erosion technique

Turbulence measurements on complicated terrains are difficult and when the interest is focused on the ground, the problem is even more complicated. A simple technique to assess wind levels near the ground is the sand erosion technique.

In this technique, described in detail by Borges and Saraiva (1979), a thin layer of sand, of small granularity, is spread uniformly over the region of interest. The wind tunnel is then operated in several different velocities for a period of time (usually from 5 to 10 minutes). After each interval, pictures are taken and stored. These pictures show patterns of clean areas and sand covered areas as shown in figure 1.

The interesting aspect of this technique is that even though qualitative in nature, quantitative results may be obtained from pictures such as those of figure 1.

The sand is displaced by a phenomenon called saltation (studied in detail by Owen, 1964). The most important parameter for saltation (and sand being blown away) is the shear velocity at the surface

$$u_\tau = \sqrt{\frac{\tau_0}{\rho}} \tag{3}$$

where τ_0 is the surface stress and ρ is the fluid density. If the sand is loose and spread on a horizontal flat surface and the grain's Reynolds number is small,

$$Re = \frac{u_\tau d}{\nu} < 5 \tag{4}$$

(d is the sand grain diameter and ν is the kinematic viscosity of the air) then the saltation will be independent of velocity profile and boundary layer thickness since it is inside the viscous sub-layer. Under these circumstances, the saltation will be characterized by the sand Froude number which is a function of Re. Borges and Saraiva (1979) determined the following expression for the saltation Froude number:

$$Fr = \frac{\rho u_\tau^2}{\rho_s g d} = 0,0180 \cdot Re^{-0,432} \tag{5}$$

In this equation, ρ_s is the sand diameter and g is the local gravity acceleration. This equation was developed using surface friction data from a jet incident on a wall. Sand is spread over a flat surface and a round jet is directed perpendicular to the surface. This flow has been extensively studied and the surface stress is known as a function of the jet center (Beltaos and Rajaratnam, 1974). This procedure is used to calibrate the sand erosion technique

Once the wind tunnel is started, the regions with shear velocity large enough to cause saltation will be cleared after being exposed to the wind for a while. This will result in contours of iso shear velocity. The contours will develop with increasing wind tunnel velocity.

Since the Reynolds number in the wind tunnel is large and the model has sharp edges it is reasonable to assume a Reynolds number independence. With this in mind, the different contours can be normalized to a given wind tunnel reference velocity and a shear velocity map on the ground can be developed:

$$u_\tau = u_\tau^0 \cdot \frac{U_{\text{reference}}}{U_{\text{picture}}} \tag{6}$$

In this equation, u_τ^0 is the shear velocity that will cause saltation (determined from eq 5), $U_{\text{reference}}$ is the reference velocity and U_{picture} is the wind tunnel reference velocity when the picture was taken.

In this experiment, the sand used has a mean diameter of $300\mu m$. The sand was manufactured by IPT's sand laboratory for use in concrete testing. From boundary layer measurements on a flat surface and observing when sand started to get blown away, it was determined that the threshold for saltation is this study is:

$$u_\tau^0 = 0,40\, m/s \tag{7}$$

The value given equation 5 results in lower shear velocity values (about $0,25\, m/s$). This discrepancy should be further studied but it is probably due to different sand properties. The surface properties where the sand is spread should not influence much since the sand grains usually have an initial upward trajectory (Owen, 1964).

5. Results

First the sand erosion results will be presented and then the hot-wire anemometry measurements.

5.1 Sand erosion

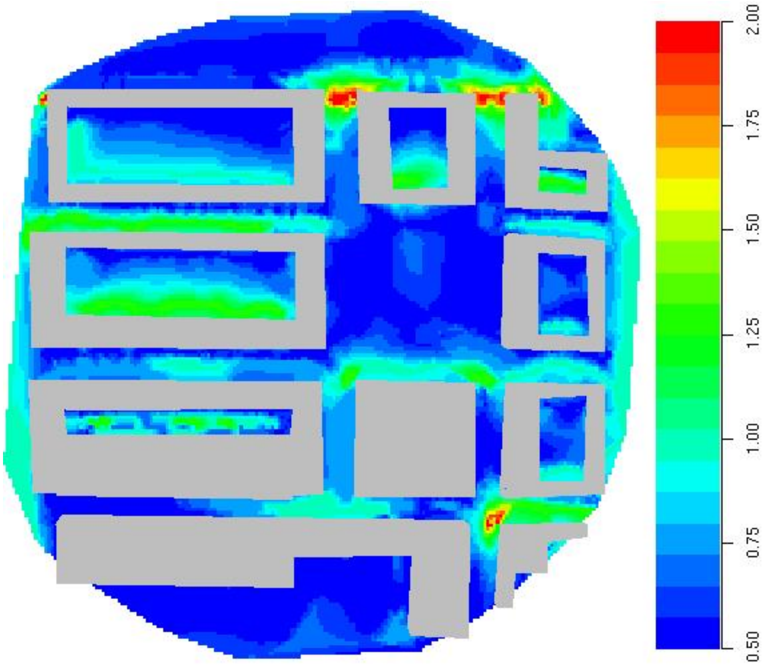

Figure 3. Shear velocity distribution $u_\tau/u_{\tau 0}$ for small model.

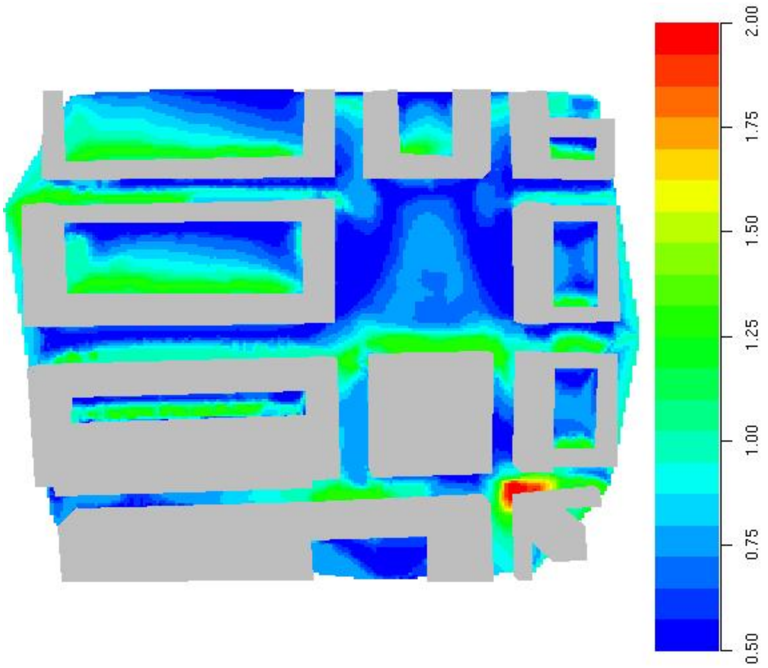

Figure 4. Shear velocity distribution $u_\tau/u_{\tau0}$ for large model.

On the larger model, only the central portion was studied due to camera zoom restrictions. Several photographs should have been used to analyze in more details of the flow.

Figures 3 and 4 present the shear velocity distribution normalized by the boundary layer shear velocity ($u_{\tau0} = 0,63\ m/s$). These figures present the same patterns but with different values of u_τ. These differences will become more evident from the turbulence measurements.

The differences observed in the u_τ contours are certainly evidences of influence of incoming boundary layer. Since the patterns are the same, if qualitative results are needed, the model scale is not that important in this case.

It should be mentioned that since the photographs of the larger and smaller model were taken with the same velocities, then according to equation 6 each wind tunnel velocity corresponds to a unique shear velocity distribution on the model. As a consequence, the velocity contours are correct only when the shear velocity is within the range $0.50 < u_\tau < 2.0$. There are values outside this range but they are not detected by the sand erosion technique and to measure them the measurements should be repeated with the wind tunnel operating in a larger velocity range.

5.2 Hot-wire anemometry measurements

Figure 5 shows the velocity profiles measure at points P1, P3, P4 and P6 (these positions are indicated in figure 1). The velocities were normalized in relation to the velocity at a reference height corresponding to the height of the highest building in the model ($160\ mm$ in the smaller model and $320\ mm$ in the larger model. The results show very good agreement. Figure 6 shows turbulence intensity profiles. They all agree very well except for point P4 where there is a small difference in the lower part of the model.

If the boundary layer over the rough surface (model) was fully developed, then the lower boundary layer could be divided in tow regions: the equilibrium boundary layer (Townsend, 1976) (log layer) and a lower region, near and within the surface elements. In the equilibrium boundary layer there is a wall similarity and the turbulence $\sqrt{u^2}$ scales with u_τ. But in this case it is still not possible to define a local roughness length z_0 and shear velocity u_τ. After the beginning of the urban canopy, an internal boundary layer grows taking place of the incoming boundary layer (Antonia and Luxton, 1971). Since it is difficult to find an appropriate u_τ inside the model, the turbulence was scaled to the local mean velocity and the results coincide for both models. The differences observed in the turbulence intensity in P4 might be a result of positioning errors because this difference was not observed in the other points even when the points where within canyons perpendicular to the main flow (as is the case for point 4). This error should be further investigated.

It is interesting to compare the velocity profiles at P2. Figure 7 presents a log-scale plot of the velocity profiles this at point. The straight lines plotted in the figure show a region of the profile with a log behavior. Since the roughness in the models change downstream, it is not easy to see this region in every profile. The interesting aspect is that the value of z_0 for the larger model calculated from this log region is approximately twice that of the smaller one. This should be expected because given a roughness density, $z_0 \sim h$ (see Raupach et al. 1991) and the roughness of the larger model is

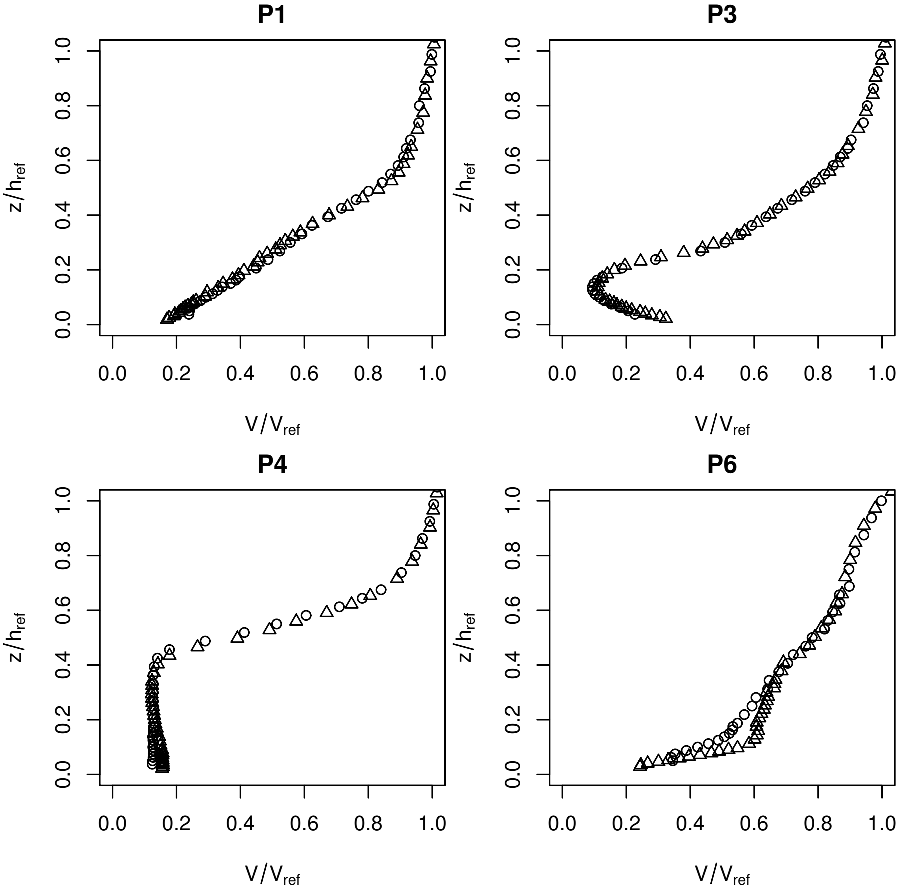

Figure 5. Velocity profiles at P1, P3, P4 and P6. Circles represent the results obtained for the small model and triangles those for the large model

twice that of the smaller one. This log region corresponds to the development of the inner boundary layer due to the new roughness. Another aspect that should be mentioned is that u_τ of the larger model is about 1.2 times that of the smaller one. This is approximately the difference of surface roughness observed in the sand erosion tests.

6. Discussion

This paper presents the first results of ongoing research on boundary layers inside urban canopies. These results show that, at least qualitatively, the behavior of the flow inside the the urban canopy is very much independent of the incoming boundary layer. It is important to remember that the roughness change in both models is very large and if the roughness of the upstream section was larger other effects would be important. For instance, in this study, the displacement thickness (the zero level of the log profile, Jackson, 1981) was 0. If this value was different, the results might have been different.

Other aspects of the flow should be further studied. A single angle is not enough. City canyons a little tilted in relation to the wind could have dramatic effects. Several other boundary layers with different canopy layout should be measured in the future.

The difficulty in this study was to interpret the shear velocity obtained by the sand erosion technique. These results were normalized by the incoming boundary layer shear velocity since a local value of u_τ is very difficult to assess or might not even exist. This results in the differences obtained for each model. For an incoming boundary layer such as the one in this test it might be possible to find an appropriate scale so that results might be corrected. In other cases this might no be easy (when there is a displacement thickness as mentioned earlier).

Since the interest of this study is in situations well within the urban canopy, using a roughness strip upstream from the model with roughness elements about the size of the buildings under study might help the wind tunnel simulations. At least it will provide a much more consistent reference shear velocity. The next step in this project is to determine the influence of several common configurations within large cities.

The boundary layers were measured using a single wire anemometer. Within the canopy the flow is extremely three-dimensional and this measurement is an approximation at best. The use of triple wire sensors could give more insight. A simple solution would be to rotate the single hot-wire probe in 3 different angles to estimate the Reynolds stresses.

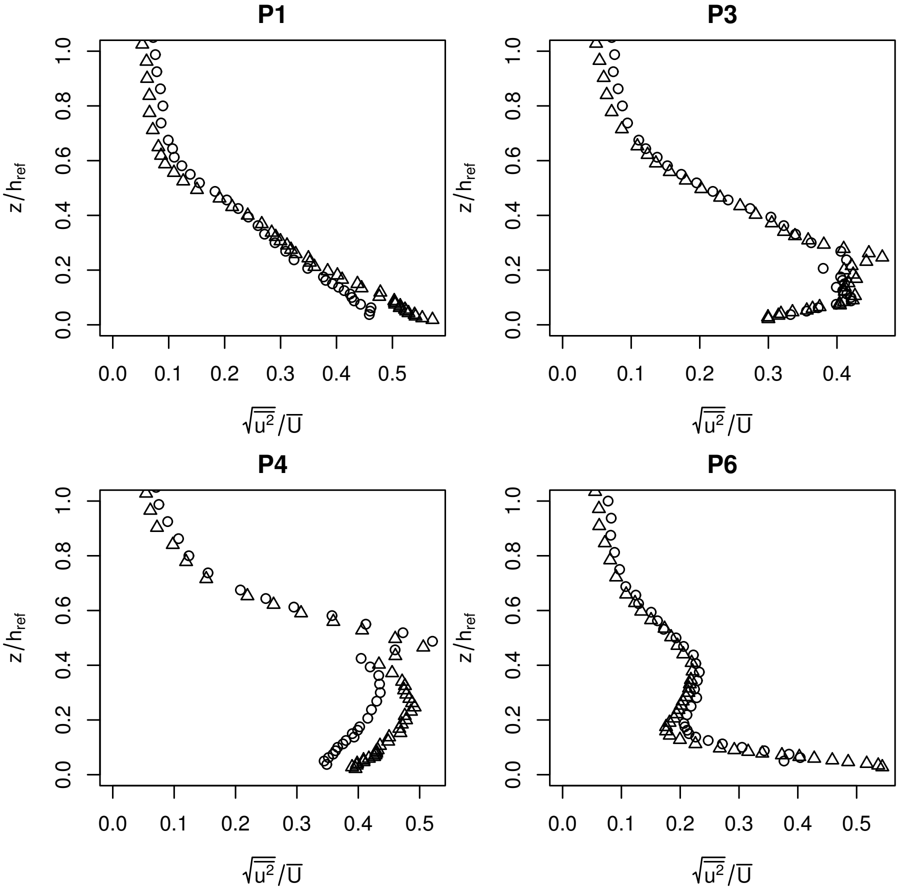

Figure 6. Turbulence intensity profiles at P1, P3, P4 and P6. Circles represent the results obtained for the small model and triangles those for the large model

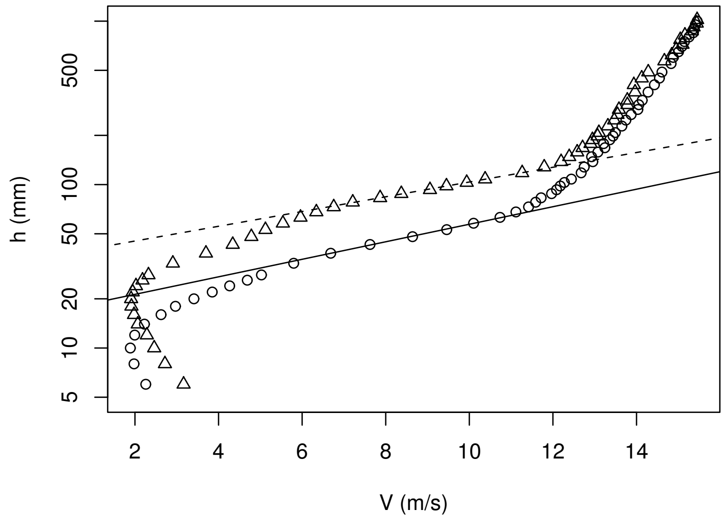

Figure 7. Velocity profiles at point P2. Circles: small model, triangles: large model, solid line: $z_0 = 17\,mm$, $u_\tau = 3.25\,m/s$, dashed line: $z_0 = 36\,mm$, $u_\tau = 3.85\,m/s$

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8. Responsibility notice