Boundary-layer response to a change in surface roughness.

James Benson

A dissertation submitted in partial fulfilment of the requirement for the degree of MSc Applied Meteorology

15th August 2005
Acknowledgements

Many thanks to my supervisor Janet Barlow for all the invaluable help and guidance during this project. A special thanks to Frauke Pascheke who spent many days teaching me the ways of Reading wind tunnel and who was always had time (and answers) for my questions. Also thanks to the lab technicians for keeping the equipment working.
Abstract

The Earth’s surface heterogeneity means that airflow is continually encountering changes in surface roughness. Previous research into the effects of these changes has shown the formation of an internal boundary layer, changing shear stresses and the turbulent response to such a change. This experiment uses a wind tunnel and hot wire anemometry to examine these aspects for a single simplified roughness change. The difficulties of investigating such features in a small wind tunnel are addressed, with consideration of surface morphology and applicability to full scale situations.

While most previous studies have considered the effect of a change in roughness length, most have neglected the effect of changing displacement height. In this experiment two surface roughness changes are investigated, both consisting of a change from upstream 3D Lego™ type roughness elements to downstream 2D bar type roughness. The downstream surface roughness bar height to canyon width ratio is different in each roughness change case providing different surface roughness and displacement height parameters. One surface provides a smooth to rough change while the other provides a rough to smooth change. The effects of both roughness changes are acceleration of the flow and reduction in shear stress over the initial bar of downstream roughness. Downstream of the roughness change the shear stress varies periodically with fetch, has a wavelength equal to the bar spacing and an amplitude that decreases with height.

Velocity profiles are found to indicate the formation of an IBL although there is insufficient fetch for an equilibrium layer to form. However by using morphometric analysis, surface parameters are estimated allowing IBL height growth theories to be compared with the IBL heights determined by gradient changes in the measured wind profile. The results of this experiment compare favourably with some theories although further experiments would be needed to confirm this is the case at longer downwind fetches. However over urban areas there is likely to be insufficient fetch for these conventional theories to be correctly applied. It is also found that within the fetch range considered in this experiment the displacement height is shown to be significant factor in determining the effect of a roughness change.
Contents

Acknowledgements ii
Abstract iii
Contents iv

List of figures and tables vi
List of figures vi
List of tables vii

Mathematical Symbols used viii

1. Introduction 1
   1.1 Motivation 1
   1.2 Objectives 1
   1.3 Structure 1

2. Theory 2
   2.1 Turbulent flow over a rough surface. 2
   2.2 Effect of a roughness change 4
      2.2.1 Introduction 4
      2.2.2 IBL depth 6
      2.2.3 Equilibrium layer depth 7
      2.2.4 Morphometric surface analysis 8
      2.2.5 Development of stress after a roughness change 12
   2.3 Wind tunnel theory 14
      2.3.1 Turbulence 14
      2.3.2 Wind profiles 17
      2.3.3 Blockage 17

3. Wind tunnel setup 18
   3.1 Apparatus 18
      3.1.1 Roughness element setup 19
   3.2 Measurement method 21
      3.2.1 Overview 21
      3.2.2 The pitot tube 21
      3.2.3 The hot wire 22
      3.2.4 The crossed hot wire 24
3.3 Measuring procedure 24
3.4 Sources of error 25
  3.4.1 Temperature 25
  3.4.2 Calibration error 25
  3.4.3 Pressure variations 26
  3.4.4 Probe positioning 26
  3.4.5 High turbulence intensity errors 26
4 Results and analysis 27
4.1 Morphometric surface roughness analysis results 27
  4.1.1 Lego™ surface roughness 27
  4.1.2 2D bar type roughness 28
4.2 Profiles above upstream Lego™ roughness 29
  4.2.1 Introduction 29
  4.2.2 Upwind boundary layer structure 31
  4.2.3 Turbulence over Lego™ surface 35
  4.2.4 Turbulence spectra 37
4.3 Profiles over R1 roughness type 38
  4.3.1 Initial flow disturbance 39
  4.3.2 Shear stress 40
  4.3.3 Turbulence response 43
4.4 R2 roughness type 46
  4.4.1 Velocity and shear stress 46
  4.4.2 Turbulent Intensity 49
  4.4.3 IBL height 51
  4.4.4 Shear stress overshoot 54
5 Conclusions 55
Appendices 59
  Appendix 1. Location of profile measurements over Lego™ surface roughness 59
  Appendix 2. Rejected Lego™ wind profiles 59
  Appendix 3. Change in normalisation wind speed with fetch 60
  Appendix 4. Log law fit using u* (IS) and average velocity profile over Lego™ 61
  Appendix 5. Errors in mean velocity and shear stress measurements 61
References 62
### List of figures and tables

#### List of figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Wind profile above a rough surface</td>
</tr>
<tr>
<td>2</td>
<td>Effect of a surface roughness change</td>
</tr>
<tr>
<td>3</td>
<td>Idealised morphometric surface roughness dimensions</td>
</tr>
<tr>
<td>4</td>
<td>Displacement height for 2D bar type roughness</td>
</tr>
<tr>
<td>5</td>
<td>Shear stress overshoot</td>
</tr>
<tr>
<td>6</td>
<td>Shear stress undershoot</td>
</tr>
<tr>
<td>7</td>
<td>Wind tunnel setup</td>
</tr>
<tr>
<td>8</td>
<td>Spires used to initiate turbulence</td>
</tr>
<tr>
<td>9</td>
<td>Lego™ roughness element dimensions</td>
</tr>
<tr>
<td>10</td>
<td>Downstream surface roughness types</td>
</tr>
<tr>
<td>11</td>
<td>Equipment setup</td>
</tr>
<tr>
<td>12</td>
<td>Wind and turbulent intensity profiles over Lego™ surface</td>
</tr>
<tr>
<td>13</td>
<td>Normalised shear stress profiles over Lego™ surface</td>
</tr>
<tr>
<td>14</td>
<td>Turbulent intensity components, $\sigma_u/U$, $\sigma_w/U$ and $\sigma_v/\sigma_u$ over Lego™ surface</td>
</tr>
<tr>
<td>15</td>
<td>Turbulent intensity components, $\sigma_u/U$, $\sigma_v/U$ and $\sigma_v/\sigma_u$ over Lego™ surface</td>
</tr>
<tr>
<td>16</td>
<td>Normalised spectral energy density distributions over Lego™ surface</td>
</tr>
<tr>
<td>17</td>
<td>Wind profiles after change in roughness from Lego™ to R1 type roughness</td>
</tr>
<tr>
<td>18</td>
<td>Flow disturbance caused by roughness change from Lego™ to R1</td>
</tr>
<tr>
<td>19</td>
<td>Normalised shear stress variations with fetch over R1 type roughness</td>
</tr>
<tr>
<td>20</td>
<td>Normalised shear stress profiles over R1 type roughness</td>
</tr>
<tr>
<td>21</td>
<td>$u^*$ values variation with fetch over R1 type roughness</td>
</tr>
<tr>
<td>22</td>
<td>Turbulent intensity $u$ component over R1 type roughness</td>
</tr>
<tr>
<td>23</td>
<td>Turbulent intensity $w$ component over R1 type roughness</td>
</tr>
<tr>
<td>24</td>
<td>Wind profiles after change in roughness from Lego™ to R2 type roughness</td>
</tr>
<tr>
<td>25</td>
<td>Normalised shear stress variations with fetch over R2 type roughness</td>
</tr>
<tr>
<td>26</td>
<td>Normalised shear stress profiles over R2 type roughness.</td>
</tr>
<tr>
<td>27</td>
<td>$u^*$ values variation with fetch over R2 type roughness</td>
</tr>
<tr>
<td>28</td>
<td>Turbulent intensity $u$ component over R2 type roughness</td>
</tr>
<tr>
<td>29</td>
<td>Turbulent intensity $w$ component over R2 type roughness</td>
</tr>
<tr>
<td>30</td>
<td>IBL growth after a change in surface roughness from Lego™ to R2</td>
</tr>
</tbody>
</table>
Figure 31  IBL growth after a change in surface roughness from Lego™ to R2 including consideration of displacement height
Figure 32  Shear stress overshoot comparison with theory

Figure 1A  Location of profile measurements over Lego™ surface roughness
Figure 2A  Rejected profiles over Lego™ surface roughness
Figure 3A  Change in normalisation wind speed with fetch over Lego™
Figure 3B  Change in normalisation wind speed with fetch over change in surface roughness from Lego™ to R1
Figure 4A  Log law fit using $u^*(IS)$ and average velocity profile over Lego™ surface

List of tables

Table 1  Coefficient for spectral density functions derived from atmospheric studies
Table 2  Geometric parameters for Lego™ roughness used in wind tunnel
Table 3  Log law parameters derived from surface form for roughness types
Table 4  Downstream roughness parameters
Table 5  $u^*/u_{\text{pref}}$, $z_0$ and $d_1$ values
Table 6  Comparison table of $u^*(IS)/u_{\text{pref}}$ values
Table 7  Differences between over bar and over canyon normalised shear stress

Table 1A  Errors in mean velocity and shear stress measurements
Mathematical Symbols used

- **a** - Overheat Ratio
- **A_F** - Frontal area (m)
- **A_p** - Element plan area (m)
- **A_T** - Lot area (m)
- **C_D** - Drag Coefficient
- **d** - Displacement height (m)
- **D_{x,y}** - Lot dimensions (x or y axis) (m)
- **f** - Frequency (Hz)
- **f_{red}** - Reduced Frequency (Hz)
- **K_m** - Turbulent exchange coefficient for momentum. (m²s⁻¹)
- **L_{x,y}** - Element dimensions (x or y axis) (m)
- **M** - Roughness change parameter
- **R_a** - Resistance of wire at ambient temperature (T_a) (Ω)
- **R_c** - Resistance of probe cable (Ω)
- **R_e** - Roughness Reynolds number
- **R_p** - Resistance of probe (including prongs) (Ω)
- **R_s** - Resistances of connection leads in probe support (Ω)
- **R_w** - Resistance of heated wire at temperature (T_w)
- **S_{uu}** - Spectral density function
- **T_{20}** - Reference temperature (20°C)
- **u** - Friction velocity (ms⁻¹)
- **u, v, w** - Velocity (x, y, z) (ms⁻¹)
- **x_F** - Fetch required for flow to be in equilibrium at height z (m)
- **z** - Height (m)
- **z_0** - Roughness length (m)
- **z_H** - Element height (m)
- **α_{20}** - Temperature coefficient of resistance at 20°C (%K⁻¹)
- **β** - Drag correction factor
- **δ** - Boundary layer depth (m)
- **δ_e** - Inner equilibrium Layer height (m)
- **δ_i** - Internal boundary Layer height (m)
- **λ_F** - Frontal area index
- **λ_P** - Plan areal fraction
- **ν** - Kinematic viscosity (m²s⁻¹)
- **ρ** - Density (kgm⁻³)
- **τ** - Turbulent momentum flux or stress (kgs⁻²)
- **Φ** - Blockage Coefficient
- **ε** - Turbulent Kinetic Energy (Jkg⁻¹)
- **u** - Mean wind velocity (ms⁻¹)
- **u_{pref}** - Mean wind velocity measured by reference pitot tube (ms⁻¹)
- **u_θ** - Mean wind velocity measured with wind incident at 0 to sensor (ms⁻¹)
1. Introduction

1.1 Motivation

The boundary layer is the part of the atmosphere directly influenced by the surface. In the horizontal plane the surface characteristics are almost constantly changing, resulting in airflow that has partially adjusted to the characteristics of many upstream surfaces. These changes can be gradual or sharp and the angle at which the wind approaches these changes is usually changing due to, for example, the prevailing synoptic conditions. In order to simplify the complexity of real life surface roughness changes a single roughness change will be setup in a wind tunnel controlled environment. It is in the boundary layer where surface based meteorological measurements are taken, and so it is essential to understand the effect of upwind surfaces to the measurement site on the results obtained. Also the dispersion of pollutants from the surface is crucially dependent on turbulence and other flow characteristics of the boundary layer, whose structure is in turn determined by the nature of the upwind surfaces.

1.2 Objectives

To investigate the effect on airflow of a change in surface roughness (and/or displacement height) using a wind tunnel. Aspects of this study include surface stress, velocity, turbulence and comparison with the features of wind tunnel, theoretical and modelling results of other authors. Standard single hot wire and crossed hot wire anemometry have been used in a small wind tunnel at Reading University. Upstream roughness was created by using Lego™ blocks and downstream roughness by street canyon type laterally arranged square bars.

1.3 Structure

This report begins with a review of applicable theory of flow over rough surfaces, the effect of roughness changes and the characterisation of a wind tunnel generated boundary layer (section 2). The experimental setup is then discussed in section 3, with a review of morphometric surface analysis methods, measurement methods and sources of error. Section 4 then presents the results and discussion, followed by the conclusions in section 5.
2. Theory

The aspects of theory that are related to this experiment are examined in this section. If the effects of a surface roughness change are to be understood it is necessary to understand the structure of the approaching flow before the roughness is encountered. Therefore the basic theory of flow over a rough surface is summarised in this section. The theoretical effect of a roughness change is then considered with sections on internal boundary layer (IBL) and equilibrium layer depth, shear stress development and the application of morphometric methods of surface analysis for estimation of surface parameters. The theoretical aspects of creating a boundary layer in a wind tunnel are also considered.

2.1 Turbulent flow over a rough surface.

Before considering the effect of a change of roughness it is necessary to examine the flow structure over a uniform area of rough surface. Rough flow is when the shear stress is dominated by the drag of the roughness elements as compared to smooth flow where the shear stress is dominated by viscosity (Raupach et al., 1991). The structure of flow over a rough surface is usually identified by the following layers (Figure 1);

1) A roughness sublayer (RS) where the velocity is horizontally inhomogeneous as the airflow is influenced by the individual roughness elements.

2) A inertial sublayer (IS) within which the flow is horizontally homogeneous and the wind varies only with height (z).

The depth of the RS is dependent on surface geometry but is usually 2-5 times the height of the roughness elements (Cheng and Castro, 2002). Within the RS there exists a canopy layer below the height of the elements themselves, where the flow is spatially inhomogeneous. The shear stress profile in the RS is also horizontally inhomogeneous, while in the IS above the shear stress is approximately constant with height (to 10% (Oke, 1987)) and horizontally homogenous, which is one assumption for the correct application of the log wind law.
By analogy with molecular diffusion the turbulent transport of momentum in the boundary layer can be described by the momentum flux.

\[ \tau = K_m \rho \frac{\partial \bar{u}}{\partial z} \]  

(1)

where \( K_m \) – turbulent exchange coefficient for momentum, or eddy diffusivity (m²s⁻¹), \( \rho \) is the density (kgm⁻³), \( \bar{u} \) is the mean windspeed (ms⁻¹).

In the RS the shear stress will decrease below the height of the individual roughness elements (Raupach et al., 1991) whilst above in the inertial sublayer the constant shear stress implies a constant wind direction and a momentum flux that is therefore one dimensional. The flow is also assumed to be horizontally homogeneous with \( \bar{u} \) varying only in the vertical. The momentum flux is equivalent to the wind stress \( (\tau_0) \) on the ground which can be also be represented by a reference velocity \( u_* \) (the friction velocity).

\[ \tau_0 = \tau = \rho u_*^2 \]  

(2)

By dimensional argument for a neutral atmosphere \( K_m \) is proportional to the product of \( u_* \) and \( z_* \) the mixing length (\( \ell \)) (Kaimal and Finnigan, 1994).

Figure 1. Wind profile above a rough surface. \( z_H \) is the roughness element height. Within the roughness sublayer the shape of the profile is dependent on the location of measurement in relation to the surface roughness elements. The Inertial sublayer is the part of the profile where shear stress is constant and the wind has a logarithmic profile with height.
\[ K_m = ku_*z \] \hspace{1cm} (3)

k is the constant of proportionality also known as the Von Karman constant \( \approx 0.4 \).

Thus by substitution of equation 2 and 3 into 1 to give the wind shear and then integrating.

\[ \bar{u} = \frac{u_*}{k} \ln \left( \frac{z}{z_0} \right) \] \hspace{1cm} (4)

Where \( z_0 \) is known as the roughness length, describing the height where the profile extrapolates to zero velocity. Depending on the nature of the surface there is a modification to the log law to account for the displacement for the flow by the surface elements.

\[ \bar{u} = \frac{u_*}{k} \ln \left( \frac{z-d}{z_0} \right) \] \hspace{1cm} (5)

This is also equivalent to the height at which the mean drag on the surface appears to act (Jackson, 1981).

A direct measure of the momentum flux is given by.

\[ \tau = -\rho \bar{u}'w' \] \hspace{1cm} (6)

Where \( u' \) is the fluctuating component of the wind in the direction of mean flow, \( w' \) is the fluctuating component of the wind normal and in the vertical. \( \bar{u}'w' \) is the covariance of the fluctuating parts. This is known as the Reynolds stress and is the mean force per unit area imposed on the mean flow by turbulent fluctuations.

### 2.2 Effect of a roughness change

#### 2.2.1 Introduction

This experiment is concerned with the response of a turbulent boundary layer to a change of surface roughness. This has been studied extensively both by wind tunnel (e.g. Antonia and Luxton, 1971; Mulhearn, 1978; Pendergrass and Arya, 1984; Cheng and Castro, 2002) and in the field (e.g. Bradley, 1968). The effect of a roughness change can be characterised by:
1) An Internal Boundary layer (IBL) developing over the new surface, growing in height with increasing distance downwind from the change.

2) A development of wind profiles, shear stress within this internal boundary layer as the flow adjusts to the new surface.

Most studies have considered a step change in surface roughness in a neutral boundary layer, which is also the topic of this study. A diagram of IBL growth is shown in Figure 2a. A typical wind profile at some distance $x$ downwind of the roughness change is shown in Figure 2b. Above the IBL the flow is characteristic of the upwind surface, while below it is affected by both the downstream and upstream roughness in the transition region. Below this is the inner equilibrium layer where the flow has adjusted to the new surface.

![Diagram of IBL growth](image)

**Figure 2.** Effect of a change in surface roughness. (a) The growth of an IBL downstream of a change in surface roughness ($x=0$). IBL depth is $\delta_i(x)$, inner equilibrium layer depth $\delta_e(x)$. (b) Velocity profiles before and after a change in roughness from smooth to rough. $\delta_1$ is the IBL depth by the extension of the downstream profile to intersection with the upwind profile. $\delta_{2i}$ is the IBL depth as determined by the point of inflection.
2.2.2 IBL depth

One particular difficulty is defining where the top of the IBL is as some authors (Cheng and Castro, 2002) take this as where the velocity reaches 99% of its upstream value, however 1% differences may be difficult to measure experimentally. Another method (Mulhearn, 1978; Bradley, 1968; Elliot, 1958) is to take the point in the log plotted profile where the downwind velocity profile merges into the upwind profile. The exact position of this ‘knee’ point is open to interpretation as shown by the difference between \( \delta_i \) – the intersection point and \( \delta_{2i} \) – the point of inflection as shown in Figure 2b. \( \delta_i \) gives a higher IBL but is dependent on obtaining a good log fit in the equilibrium layer which may be may not be that deep depending on fetch and roughness geometry (see section 2.2.3). The point of inflection method \( (\delta_{2i}) \) has the disadvantage of being indistinct in situations where there are small differences in downwind and upwind profiles. Antonia and Luxton (1971) argued from theoretical grounds that plotting \( u \) vs. \( z^{1/2} \) gives linear profiles of the upstream and downstream profiles whose intersection marks the IBL height.

Another method of obtaining the IBL height is via stress measurements, for example the height where there is a 1% increase compared to the upstream value at the same height for a SR change. This usually tends to give a larger IBL height in comparison to the velocity method as stress adjusts faster than velocity profiles.

The evolution of IBL height with fetch has been reviewed by Walmsley (1989) and Savelyev and Taylor (2005) with comparisons to wind tunnel and field data. They find that there is a large variation of heights predicted. Elliot (1958) used the following empirical formula;

\[
\delta' = \frac{\delta}{z_{02}} = (0.75 - 0.03M) \left( \frac{x}{z_{02}} \right)^n
\]  

(7)

where \( M = \ln \left( \frac{z_{02}}{z_{01}} \right) \) describes the ‘strength’ of the roughness change, \( n = 0.8 \) and the subscripts 1 and 2 refer to upstream and downstream respectively. The dependence on M in this formula is weak and thus this expression is frequently used in an M independent form \( M=1 \) (Walmsley, 1988).
\[ \delta' = \frac{\delta}{z_{02}} = 0.72 \left( \frac{x}{z_{02}} \right)^n \] (8)

Elliot's (1958) formula (equation 7) agrees well with Bradley's (1968) smooth to rough (SR) and rough to smooth (RS) transitions, and also Antonia and Luxton's (1972) SR experiment (Kaimal and Finnigan, 1994). However Antonia and Luxton (1972) found for their rough to smooth study that the n coefficient was ~ 0.43.

Wood (1982) uses a similar formula, arguing that only the rougher surface is important.

\[ \frac{\delta_i}{z_{0r}} = 0.28 \left( \frac{x}{z_{0r}} \right)^{0.8} \] (9)

Where \( z_{0r} = \max(z_{02}, z_{01}) \). It is also noted that Wood (1982) considered his formula only valid up to \( \delta_i/\delta = 0.2 \) where \( \delta \) is the depth of the boundary layer in which the IBL develops.

Another approach is to use a ‘diffusion analogy’ approach assuming that the growth of IBL is analogous to the spread of a passive contaminant (Miyake, 1965; Savelyev and Taylor, 2005). From this reasoning Panofsky and Dutton (1984) obtained the following formula for IBL depth.

\[ 1.25k \frac{x}{z_{02}} = \frac{\delta_i}{z_{02}} \left( \ln \frac{\delta_i}{z_{02}} - 1 \right) + 1 \] (10)

### 2.2.3 Equilibrium layer depth

The inner equilibrium layer is usually taken as the lowest 10% of the IBL (Kaimal and Finnigan, 1994), and is a constant stress layer in equilibrium with the new surface. Wieringa (1993) presents an equation for the fetch needed \( (x_F) \) to ensure that the flow at height \( z \) is in equilibrium with the new surface based on this 10% assumption.

\[ x_F = 2z_{02} \left[ \frac{10(z - d_z)}{z_{02}} \left( \ln \left( \frac{10(z - d_z)}{z_{02}} - 1 \right) + 1 \right) \right] \] (11)
However if there is insufficient fetch then this equilibrium layer may not extend above the RS and so be difficult to identify due to the spatial inhomogenities in flow caused by the roughness elements as found by Cheng and Castro (2002). To obtain the log law parameters a constant stress equilibrium layer is required and so to obtain these for a surface with no such equilibrium layer a morphometric method of surface analysis can be used.

### 2.2.4 Morphometric surface analysis

The surface drag depends on the layout and size of the roughness elements, which in turn can be formulated to give directly the $z_0$ and $d$ parameters. A review of such morphometric methods is provided by Grimmond and Oke (1999), Macdonald et al. (1998).

These methods consider the geometry as shown in Figure 3 and are divided into 3 general approaches;

1) Height based.

2) Height and plan areal fraction $\lambda_p = \frac{A_p}{A_r} = \frac{L_x L_y}{D_x D_y}$ based.

3) Height and frontal area index $\lambda_f = \frac{A_p}{A_r} = \frac{z_{HF} L_y}{D_x D_y}$ based.

**Figure 3. Idealised morphometric surface roughness dimensions.**
3D roughness geometry

To calculate \( z_0 \) and \( d \) the simplest method of estimation is a ‘rule of thumb’ approach:

\[
\begin{align*}
  z_0 &= 0.1 \bar{z}_H \quad \text{(12a)} \\
  d &= 0.7 \bar{z}_H \quad \text{(12b)}
\end{align*}
\]

where coefficients 0.1 and 0.7 are chosen by Grimmond and Oke (1999) as a representation of results of wind tunnel and field studies. The major limitation of this height based approach is that it does not take roughness element density into account, but the coefficients can be changed depending on what surface is being studied.

Early studies by Lettau (1969) used data obtained by from the field experiments of Kutzbach (1961) that used bushel baskets placed in a regular grid on a frozen lake, giving:

\[
\begin{align*}
  z_0 &= 0.5 \bar{z}_H \lambda_F \\  d &= 0.463 - 0.4352 \lambda_F \quad \text{(13)}
\end{align*}
\]

This expression starts to fail when \( \lambda_F \) increases beyond 20 – 30% (see discussion of Macdonald et al. 1998) due to the interaction of air flow between each obstacle and consequent development of a non-zero displacement height. Also as it is based on results obtained using bushel baskets in regular arrangement it is in principle limited to that specific element type and arrangement.

Counihan (1971) used a height and plan areal fraction method where:

\[
\begin{align*}
  z_0 &= (1.08 \lambda_p - 0.08) \bar{z}_H \quad \text{(14a)} \\
  d &= [1.4352 \lambda_p - 0.0463] \bar{z}_H \quad \text{(14b)}
\end{align*}
\]

These equations describe the results obtained in wind tunnel experiments using Lego™ elements on a Lego™ base board and so has specific application to the current experiment. Counihan (1971) considered the limits of equation 14(a) to be \( 0.1 < \lambda_p < 0.25 \). The lower limit was chosen because \( z_0 \) is very dependent on element spacing, and the possibility that measurements made would be of an elements individual wake flow rather than of the
boundary layer flow produced by the roughness elements. Consequently it was found that at low density arrangements it was possible to determine a $z_0$ for the baseboard and a separate $z_0$ for the roughness elements. In those cases Counihan (1971) presents a spatial average to ensure that both effects are accounted for. However as considered earlier in section 2 this spatial inhomogeneity is expected in the RS and so $z_0$ and $d$ values should ideally be obtained from measurements in the IS. Above 0.25 the results obtained were distinctly non linear and no curve was fitted, although Grimmond and Oke (1999) do fit a curve based on Counihan’s (1971) results that covers $\lambda_p = 0$ to 0.5

$$z_0 = \left(C_1 + \sum_{j=2}^{j=10} C_j \lambda_P^{-1}\right) z_H$$

(14c)

Where $C_1=0.02677$, $C_2=1.3676$, $C_3=15.98$, $C_4=387.15$, $C_5=-4730$, $C_6=32057$, $C_7=-124308$, $C_8=-124308$, $C_9=27162$, $C_{10}=-310534$, $C_{10}=14444$

Macdonald et al. (1998), starting from fundamental principles, derived formulas for $z_0$ and $d$ (equation 15a,b) that are applicable to higher densities ($\lambda_P$, $\lambda_F$) and which show behaviour consistent with experiments (Counihan, 1971). For instance, for increasing densities $z_0$ begins to decline after a peak, as would be expected with the development of skimming flow over the elements. This method allows for corrections for turbulence, velocity profile, flow incidence and rounded edges and is considered applicable to both 2D and 3D elements.

$$d = z_H \left(1 + \alpha^{-\lambda_P} (\lambda_P - 1)\right)$$

(15a)

$$z_0 = z_H \left(1 - \frac{d}{z_H}\right) \exp\left\{-\left[0.5 \beta \frac{C_D}{k^2} \left(1 - \frac{d}{z_H}\right) \lambda_P^{-0.5}\right]\right\}$$

(15b)

$\alpha$ - An empirical coefficient obtained from evaluation of wind tunnel data
  - $= 4.43$ for staggered array of roughness elements (Macdonald, 1998)
  - $= 3.59$ for square (regular) array of roughness elements (Macdonald, 1998)

$C_D$ - Drag coefficient, depends on dimensions of surface elements (ESDU, 1986)

$\beta$ - Drag correction factor, accounts for velocity profile shape, turbulence, flow incidence, rounded edges (ESDU, 1986)
2D roughness geometry

There has also been a large amount of research into the effect of flow over 2D bar canyon type roughness by both modelling (Sini et al., 1996; Leonardi et al., 2003) and by analysis of wind tunnel experiments (Oke, 1987). The streets are usually considered in terms of their height to width ratio (=z_h/W_s). Oke (1987) describes 3 regimes of flow associated with this type of roughness;

1) Isolated flow – Bar rows far enough apart for the flow to be the same as that for isolated buildings for z_h/W_s < 0.3.
2) Wake interference flow – Wake from upwind bar interferes with downstream bar’s flow pattern for 0.3 < z_h/W_s < 0.65
3) Skimming flow – Flow skims over top of bar creating vortex in canyon for z_h/W_s >0.65

Work on the relation between these flow regimes and the 2D roughness elements has been reviewed by Raupach et al. (1991) showing the experimental data of Kader (1977) with a maximum roughness length at z_h/W_s =0.25. This corresponds closely to the z_h/W_s = 0.3 transition from isolated to wake interference flow as found by Oke (1987). Jackson (1981) considered that as the bars become closer together (large z_h/W_s) z_0 decreases and d increases, approaching the height of the bar (z_h). This is confirmed by numerical model results of Leonardi et al. (2003) (Figure 4).

![Figure 4. Displacement height for 2D bar type roughness. Numerical model results of Leonardi et al. (2003).](image-url)
2.2.5 Development of stress after a roughness change

One of the first studies of surface stress after a change in roughness was a field experiment by Bradley (1968) using drag plates. This method allowed direct measurement of the surface stress for both smooth to rough and rough to smooth changes with surfaces of tarmac and spikes. The results for the smooth to rough change show an ‘overshoot’ in stress, followed downstream by a transition to a new equilibrium stress value (Figure 5). This may be explained by the airstream generating high stress upon encountering the new roughness, followed by the velocity close to the ground falling and a subsequent reduction in surface stress.

Figure 5. Shear stress overshoot in a S-R surface roughness change as measured in experiments of Bradley (1968) and predicted by model results of Rao. $z_01 = 0.002$ cm, $z_02 = 0.25$ cm. (From Rao et al., 1974)

Figure 6. Shear stress undershoot in a R-S surface roughness change as measured in experiments of Bradley (1968) and predicted by model results of Rao et al. (1974) A. $z_01 = 0.25$ cm, $z_02 = 0.002$ cm. B. $z_01 = 0.25$ cm, $z_02 = 0.0002$ cm. (From Rao et al., 1974)
In the rough to smooth case the surface stress ‘undershoots’, and then gradually returns to equilibrium value although this is slower than in the smooth to rough case (Figure 6) (Kaimal and Finnigan, 1994). Both the S-R and R-S surface roughness changes in Bradley’s (1968) experiment involved very large changes in surface roughness \( M = \pm 4.83, \text{ i.e. } z_{02} = 125*z_{01} \) which are very difficult to recreate in a wind tunnel situation due to the relative size of the elements required and limited depth of boundary layer generated in a wind tunnel. Antonia and Luxton (1971) in wind tunnel experiments measured surface stress using pressure tapping of the roughness elements on the downwind and upwind faces. The size of the holes drilled did however limit the resolution and the pressure differences were small and so large errors occurred. However the results also supported the existence of a shear overshoot (using crossed hot wire anemometry) for a smooth to rough change although not as pronounced as in Bradley’s (1968) results. Pendergrass and Arya (1984) results also confirmed the existence of a shear stress overshoot but only at one particular measurement height. Cheng and Castro (2002) in a wind tunnel study concluded that the existence of a shear stress overshoot was dependent on the location at which the shear stress was measured in relation to the roughness elements. Their experiment was did however rely on cross wire measurements rather than the direct measurement techniques of Bradley (1968), Antonia and Luxton (1971) and so is very dependent on the height or range of heights from which the shear stress is measured. The particular pattern of shear stress measured by Cheng and Castro (2002) was due to the choice of 2D bar type elements, leading to fluctuating shear stress values of wavelength equal to the spacing between roughness elements, with the amplitude of these fluctuations decreasing at greater heights.

Other more theoretical studies have been done to examine the overshoot and undershoot phenomena, for example Rao et al. (1974) used a 2nd order turbulence closure to model this effect. This study did not link shear stress and shear by an eddy diffusivity (as in equation 1) and therefore performed well in a non local equilibrium situation such as after a roughness change, with good agreement with Bradley’s (1968) results (Figure 5 and 6). Another theory of shear stress development uses the assumption that there is a sharp change of wind profile at the IBL top (Jensen, 1978) leading to the following expression.
\[
\frac{\tau_2}{\tau_1} = \left[ 1 - \frac{M}{\ln \left( \frac{\delta_i}{z_{02}} \right)} \right]^2
\]  

(16)

By consideration of the effect of displacement height Barlow (personal communication) obtained:

\[
\frac{\tau_2}{\tau_1} = \left[ \ln \left( \frac{\delta_i - d_1}{\delta_i - d_2} \right) \right] + 1
\]

(17)

It will not be possible to measure the IBL height accurately because the shear overshoot occurs as the new roughness surface is encountered and the IBL depth is very small at this point. Therefore \( \delta_i \) is obtained from the theories of section 2.2.2 and so this shear stress ratio is critically dependent on the accuracy of those theories.

### 2.3 Wind tunnel theory

The use of a wind tunnel for this study is based on a need to simplify the complexity of real life roughness changes in order to make the characteristic features of such a change more identifiable. Also to properly ascertain what changes do occur is necessary to study the boundary layer structure to a depth many times the height of the roughness elements. In a full scale experiment this would very difficult as many very tall observation masts would be needed at considerable effort and cost, and these would still not allow the measurements at the many points that may be of interest to this study. Therefore a wind tunnel provides a convenient platform for studying a change in surface roughness. However in order for the results to be comparable to an atmospheric study the wind tunnel boundary layer should have characteristics of a atmospheric boundary layer. The following guidelines (VDI, 2000) have been considered;

#### 2.3.1 Turbulence

A Wind tunnel boundary layer has to be turbulent, so the surface of the wind tunnel has to be aerodynamically rough. Using the roughness Reynolds number (equation 18) smooth flow is
when $Re_* < 5$ and fully rough flow is considered as $Re_* > 70$ (Garratt, 1992; Raupach et al., 1991). At high enough Reynolds number the structure of the turbulence in the inertial sublayer is similar no matter what roughness type the surface is. Thus the turbulent features of the atmospheric boundary layer obey this similarity in the wind tunnel providing the roughness Reynolds number is large enough (> 5).

$$Re_* = \frac{u_* z_0}{\nu}$$  \hspace{1cm} (18)

Where $\nu$ - kinematic viscosity

Firstly, spectral analysis of the fluctuations of each velocity component $u$, $v$, $w$ can be compared to known atmospheric results as described in VDI, 2000 (Table 1). The energy spectra allow examination of what the size of the main energy containing eddies by measurement of the flow at one point. This is possible by reference to Taylor’s hypothesis, which considers that the turbulence is ‘frozen’.

$$\frac{f S_{uu}(f, z)}{\sigma_u^2(z)} = \frac{Af_{red}}{(E + Bf_{red}^c)^D}$$  \hspace{1cm} (19)

where $f$ - frequency of velocity fluctuations
$S_{uu}(f, z)$ - spectral density distribution function of component $u$
$f_{red}$ - reduced frequency
$A...E$ - approximation constants
$\sigma_u(z)$ - standard deviation of the fluctuation component of $u$

<table>
<thead>
<tr>
<th>Constants</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>$f_{red}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$u$</td>
<td>16.8</td>
<td>33.0</td>
<td>1</td>
<td>5/3</td>
<td>1</td>
<td>$\frac{f^2}{\bar{u}(z)}$</td>
</tr>
<tr>
<td>Kaimal et al. (1972)</td>
<td>2.8</td>
<td>9.5</td>
<td>1.00</td>
<td>1</td>
<td>2/3</td>
<td>1</td>
</tr>
<tr>
<td>$w$</td>
<td>0.35</td>
<td>5.3</td>
<td>1.67</td>
<td>1</td>
<td>1</td>
<td>$\frac{f^2}{\bar{u}(z)}$</td>
</tr>
</tbody>
</table>

Table 1. Coefficient for spectral energy density functions derived from atmospheric data (VDI 2000).
Secondly, the standard deviation (σ) of the fluctuating components \( u', v', w' \) can be used as a measure of turbulent intensity by

\[
I_i(z) = \left( \frac{\sigma_i^2}{\bar{u}(z)^2} \right)^{\frac{1}{2}} = \frac{\sigma_i}{\bar{u}} ; i = u, v, w
\]

(19)

The ratio of the standard deviations of each component can be approximated by \( \sigma_u: \sigma_v: \sigma_w = 1: 0.75 :0.5 \) (VDI, 2000). The variation of turbulent intensity with height is dependent on the turbulent kinetic energy (equation 20) and the velocity at that height \( \bar{u}(z) \).

\[
\frac{TKE}{kg} = \bar{\varepsilon} = 0.5\left( \bar{u}^2 + \bar{v}^2 + \bar{w}^2 \right)
\]

(20)

The creation and dissipation of TKE in a neutral stability wind tunnel is described by the TKE budget (equation 21)

\[
\frac{\partial \bar{\varepsilon}}{\partial t} = S - A - D + T
\]

(21)


As the surface is approached there are larger values of turbulence intensity due to increased shear production of TKE. In an equilibrium flow situation this is balanced by the dissipation and transport terms. The energy contained in the mean flow, the mean kinetic energy (MKE) (equation 22) is has a similar energy balance except the shear term has the opposite sign and so an increase in shear generated TKE leads to a reduction in the MKE of the flow and therefore the velocity components;

\[
\frac{MKE}{kg} = 0.5\left( \bar{u}^2 + \bar{v}^2 + \bar{w}^2 \right)
\]

(22)

Therefore close to the surface high turbulence intensities are combined with reduced mean velocity components.
2.3.2 Wind profiles

Near the ground the log wind law can be used (equation 5). The profiles should be measured at the upstream and downstream ends of the part of the wind tunnel under test for comparison purposes. This is because the boundary layer produced in the wind tunnel should be in equilibrium with the surface, that is, the velocity profiles, and turbulence characteristics should not change significantly with fetch. Establishing an equilibrium part of the flow allows changes brought about by the change in roughness to be resolved from changes that might occur due to the changing nature of a non equilibrium flow.

2.3.3 Blockage

If elements of roughness are large then the flow may be excessively constricted by the tunnel walls leading to increased pressure gradient and consequent acceleration of flow at the blockage. A blockage coefficient is defined as

\[
\Phi = \frac{A_{proj}}{A_{wt}}
\]  

(23)

where \( A_{proj} \) – projected area of obstacle along main wind direction. 
\( A_{wt} \) - wind tunnel cross-sectional area.

The limit set by VDI (2000) is \( \Phi < 5\% \) for enclosed measurement sections.
3 Wind tunnel setup

The setup of the wind tunnel determines how the boundary layer is created in this study. The appropriate use of the available apparatus and the individual limitations of each item of equipment is what will limit the overall accuracy of the results obtained.

3.1 Apparatus

The wind tunnel comprises a working section 232x232x1500mm, with wind control provided by a sucking fan operated via a transformer. Access is gained to the working section by removable top sections, with one part having a 30cm long slot for hot wire entry. One pitot tube for reference velocity measurements is located at (j), while another for use for hotwire calibration is located at (k) (Figure 7).

To recreate the atmospheric boundary-layer in the wind tunnel with the limited fetch available it is necessary to use an artificial method (Cook, 1978) rather than let one grow naturally. Here this is in the form of spires in the arrangement shown in Figure 8. These initiate turbulence producing a boundary layer of sufficient depth for experimentation. The roughness elements work in conjunction with the spires, having the same role as in a naturally grown boundary layer. They provide a drag on the wind such that a profile of Reynolds stress is established which in turn controls the mean velocity profile and turbulence characteristics,
and thus $u^*$, $d$ and $z_0$ (Cook, 1978). To check how well the wind and turbulence profiles approximate the atmospheric boundary layer the criteria of the previous section were used.

![Figure 8. Spires used at intake to wind tunnel to generate turbulence](image)

3.1.1 Roughness element setup

The roughness elements used in the wind tunnel consist of standard Lego™ blocks arranged in a staggered arrangement on a Lego™ board surface (Figure 9). The difficulty with this is that there may in fact be 2 contributions to the surface roughness: the Lego™ block elements and the Lego™ board surface. For the purpose of morphometric analysis $z_{hl} = 9.6\text{mm}$ as the protrusions on top of the element are considered to exert minimal drag on the flow (due to their size and rounded shape) compared to the main body of the element. However in all other discussion the element height includes these protrusions and is therefore $z_{hl} = 11.5\text{mm}$.

The downstream roughness types (Figure 10) will consist of rows of streets made with rectangular bars 12.6 mm tall and 12.6mm wide extending across the wind tunnel width. This roughness has a surface level 1.7mm above that of the Lego™ surface. The choice of a 2D roughness type means that it provides an instantaneous change in roughness in comparison to 3D elements which due to the gaps between elements, would result in horizontally (along y axis) inhomogeneous velocity, stress and turbulence statistics. This would require spatial
averaging of the results within the RS and greater effort in measurement setup. Also this spatial inhomogeneity would make the anticipated roughness change effects less discernable.

Figure 9. Lego™ roughness element dimensions. The dashed region represents the plan area

Figure 10. Roughness types for downstream of change. (a) R1. (b) R2.
3.2 Measurement method

3.2.1 Overview

The equipment setup is shown on Figure 11 using labels from Figure 7. Both the pitot tubes and HW anemometer have an analogue signal output that is fed firstly into a connector box and then converted into a digital signal by an interface card in the computer. Once converted this signal is analyzed by the labview software for calibration and result taking purposes.

![Figure 11. Equipment setup. Labview software developed by Environmental Flow Research Centre (ENFLO). CTA – Constant temperature anemometer.](image)

The next sections consider each element in Figure 11 and its use in this study.

3.2.2 The pitot tube

A pitot tube measures velocity using the following principles, assuming dynamic pressure at low velocities $P_d = \frac{\rho U^2}{2}$;

$$U = \left(2 \left(\frac{P_i - P_s}{\rho}\right)\right)^{1/2}$$

(24)

static pressure ($P_s$) + dynamic pressure ($P_d$) = total pressure ($P_i$)

(25)
Calibration of pitot tubes

The pressure transducer (manometer) measures the difference in pressure $P_t - P_s = \Delta P$ and displays this in mmH$_2$O. To calibrate the pitot tube, 8 point measurements are taken at different tunnel speeds, with user inputted $\Delta P$. The voltage output from the manometer has a linear relationship to the mmH$_2$O display, thus the Labview software calculates a best fit line from the user inputted values and those from the voltage input. This best fit line describes the response of the pitot tube allowing voltage to be converted into velocity with equation 24. The pitot tube is not accurate at very low wind speeds so points are taken at wind tunnel speed from 4 - 12 ms$^{-1}$. The sampling rate for these points is 1000Hz for a 20 second period. To try and minimise turbulent fluctuations the spires are removed during calibration. The height of each calibration is $z = 178$mm to avoid the influence of the surface and is kept the same in all calibrations.

This procedure is repeated with the reference pitot tube and FC016 ±200mmH$_2$O. This manometer is not as accurate as the FC016 ±20mmH$_2$O as it only uses a small part of its range as it is meant for use at higher velocities.

3.2.3 The hot wire

The principle of hot wire anemometry is that airflow over a wire produces a cooling effect via conduction into the air immediately surrounding it and subsequent convection and advection of this air away from the wire. With constant temperature hot wire anemometry the temperature of the wire is kept constant by a feedback differential amplifier, thus allowing rapid variation of the heating current to compensate for instantaneous changes in the flow velocity. A single normal tungsten hot wire is used which means that the hot wire is at 90 degrees to mean flow direction.

The main consideration in operation is that a high wire temperature gives high velocity sensitivity but as the tungsten wire element of the hot wire oxidises at around 350°C the temperature of the wire ($T_w$) must remain below this. (Bruun, 1995) The setting of the wire temperature depends on the overheat ratio ($a$):

$$a = \frac{R_w - R_o}{R_o}$$

(26)
where  \( R_w \) - Resistance of heated wire at temperature \((T_w)\)
\( R_a \) - Resistance of wire at ambient temperature \((T_a)\)

When setting the overheat ratio the probe \((R_p)\), probe prongs \((R_p)\) and cable resistance \((R_c)\) must be taken into account;

\[
R_L = R_p + R_s + R_c
\]

where  \( R_s \) – Resistances of connection leads in probe support
\( R_c \) – Resistance of probe cable
\( R_p \) – Resistance of probe (including prongs)

For this experiment the total lead resistance - \( R_L \) is assumed to be 0.1\( \Omega \)

Thus the total resistances are:

\[
\begin{align*}
R_{am} &= R_a + R_L \\
R_{wm} &= R_w + R_L
\end{align*}
\]  

(27a)  
(27b)

The temperature of the wire is given by:

\[
T_w - T_a = \alpha \frac{a}{\alpha_{20}}
\]  

(28)

where  \( \alpha_{20} \) – Temperature coefficient of resistance at 20\( ^\circ \)C (~ambient temperature)

The single HW used in this experiment has \( R_a \)=8.270 \( \Omega \), \( \alpha_{20} \)=0.36\%K\(^{-1}\) and when operated at an overheat ratio of 0.6 thus has \( R_w \)=13.3 \( \Omega \) and an operating temperature of 242\( ^\circ \)C.

**Calibration**

The output from the anemometer is first fed into an amplifier system with gain, low pass filter settings and a zero-offset dial (see Figure 11). This allows the input voltage into the computer interface card to be set within the input range, including the spikes and troughs of voltage associated with a fluctuating turbulent flow. The low pass filter is set to half the required frequency according to Nyquist criterion to avoid aliasing of high frequency components (Kaimal and Finnigan, 1994). Therefore if sampling is at 3200Hz the low pass filter is set to 1600Hz. This voltage input is then calibrated against the pitot tube which is located at the same height (169mm) and fetch (1245mm) and offset laterally 38.5mm.
The output voltage $E = F(U)$ into the computer obeys King’s power law (Kaimal and Finnigan, 1994)

$$E^2 = A + BU^n$$  \hspace{1cm} (29)

where $A$, $B$, $n$ are coefficients determined by calibration and $n \sim 0.45$ but can use an optimal value that gives the best goodness of fit or lowest normalised standard deviation $\varepsilon_u$.

### 3.2.4 The crossed hot wire

To obtain measurements of the covariance $\overline{u'w'}$ and therefore the shear stress it is necessary to have simultaneous measurements of both $u$ and $w$ components within a small measurement volume. A Dantec dynamics P61 crossed hot wire is used in this experiment.

The crossed hot wire has 2 wires perpendicular to each other. Each wire works independently following the same principles to the single wire above. However when processing the voltages from the 2 wires it is possible to break down the signal into its component parts $u$, $v$ or with 90 degree rotation of the hot wire, the $u$, $w$ components. To do this it is necessary to add an additional calibration procedure known as an angle calibration. Here calibration points are taken at different incidences to the mean flow, e.g. from $-25$ to $+25$ degrees from the mean flow vector. This calibration was only followed once during this experiment as the angle between the wires should not change between each measurement day.

### 3.3 Measuring procedure

Calibration of the pitot tubes and hot wire was nominally done once a day, as this calibration can be adjusted by providing updated temperature and pressure measurements into the Labview software at regular intervals (at the beginning of each profile in this experiment). This correction is however only useful up to a change of 5°C from the calibration temperature (Jørgensen, 2002). To ensure that the main energy containing range of turbulent spectra is sampled measurements are taken at a sampling rate of 3200Hz with low pass filter at 1600Hz. Different sampling periods were tested and a sampling period of 2 minutes was found to allow second order statistics such as $\overline{u'^2}$ to reach a stable value and so was used throughout the experiment.
Profile measurements were taken at logarithmic spacing of height $z$ and where possible at the same height intervals for each profile upwind and downwind of the roughness change. This allows results at the same height to be compared with varying fetch. The hot wire is located in a laterally central position (116mm from the tunnel sidewalls) and can be adjusted to any fetch within the measurement section. Profile measurements were taken at varying fetches. Due to the staggered nature of the roughness elements this allows a spatial average of the profile parameters within the RS (Appendix 1). This should also reveal if there are any variation of profiles with fetch $x$. Due to the size of the probe it was not possible to measure profiles in the canopy layer directly in front of a Lego™ element and profiles behind Lego™ elements sometimes required the removal of a Lego™ element downstream to facilitate access to canopy layer element height velocity measurements. As well as the upstream profiles, additional profiles were taken at fetches greater than $x = 1032$mm where the new roughness was to be located for comparison purposes with the profiles obtained when it is in place.

### 3.4 Sources of error

Overall error is typically 3% for velocity measurements. The most important contributions to this are from the calibration, linearization and temperature errors. These are described in the following sections.

#### 3.4.1 Temperature

This is usually the most important source of error, of approximately 2% in wind velocity $1^\circ$ change in temperature for a wire operated at overheat ratio of 0.8. This can be accounted for after calibration although temperature measurements need to be taken regularly. For example in the morning when the room’s temperature may be varying rapidly one profile of 16 samples each of 2 minutes duration will take approximately 45 minutes, which is enough time for a large temperature rise ($\sim 1^\circ$C) and error to occur.

#### 3.4.2 Calibration error

The error due to calibration is due to the error associated with the pitot tube pressure measurement. A resolution of 0.01 mmH$_2$O corresponds to an error of 0.1% at the operating speed of this experiment ($\sim 8$ms$^{-1}$). This error would however be significant at lower velocities. There are also curve fitting errors (linearization errors) which occur during calibration and are usually measured in terms of normalised standard deviation $\varepsilon_u$. For the
single wire the average curve fitting error of all calibrations was $\varepsilon_0 = 0.22\%$, and for the cross wires $\varepsilon = 0.13\%$ and $\varepsilon_u = 0.2\%$ for pitot tube calibrations.

### 3.4.3 Pressure variations

It is important to re-zero the manometers after each profile otherwise the velocity measurements will be subject to a gradual drift during a day’s experimentation. Also calculation by the software of the hot wire velocity is also sensitive to pressure variations due to changes in density that affect the mass transfer ($\rho U$), and therefore heat transfer over the hot wire. The pressure variation error is typically 0.6% for the pressure fluctuations experienced during one day’s experiment. This effect is however minimised due to the inputting of ambient pressure into the Labview software before each profile during measurements.

### 3.4.4 Probe positioning

As long as the hot wire is kept in the same position as during calibration and measurement this error is likely to be negligible. If however there is misalignment with the pitot tube during calibration then a systematic error will be present in that day’s results. However this should only be small as the eye is estimated be able to judge perpendicular angles $\pm 2^\circ$, or equivalently as $u_\theta$ varies as $u(1-\cos \theta)$, a 0.5% error at standard tunnel free stream operating speed (8ms$^{-1}$) (Jørgensen, 2002).

### 3.4.5 High turbulence intensity errors

Cross wire anemometers are subject to additional errors may occur when the velocity is incident on the hot wire at an angle outside the acceptable range. Also there are effects due to sheltering of the flow to one wire by the other wire in high turbulence intensities. This generally becomes significant at turbulent intensities over 0.2. The effect causes a cross wire to overestimate the mean wind speed and underestimate the Reynolds stress (Tutu and Chevray, 1975). For example a turbulence intensity of 0.3 then the shear stress is underestimated by approximately 25%, and the mean velocity overestimated by 7% (Tutu and Chevray, 1975). Error estimates for other turbulent intensities are given in Appendix 5. These errors could be corrected for but their calculation for all the results is beyond the scope of this project.
4 Results and analysis

The results of profile measurements at different fetches over two different roughness changes R1 and R2 are presented here. Firstly the upwind (Lego™) and both downwind (R1 and R2) surfaces $z_0$ and $d$ values are calculated using morphometric analysis to allow comparison with those obtained by measurements. The upwind surface velocity and shear stress and turbulence properties are discussed, followed by the corresponding results with increasing fetch after the roughness changes to both R1 and R2. The IBL height and shear stress ratios are then calculated and compared to various theories.

4.1 Morphometric surface roughness analysis results

4.1.1 Lego™ surface roughness

Table 2 gives the $\lambda_p$, $\lambda_F$, $\bar{z}_H$ for the Lego™ elements and base board separately.

<table>
<thead>
<tr>
<th>Surface</th>
<th>$\bar{z}_H$ (mm)</th>
<th>$\lambda_p$</th>
<th>$\lambda_F$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lego™ elements</td>
<td>9.6mm</td>
<td>0.0713</td>
<td>0.088</td>
</tr>
<tr>
<td>Lego™ baseboard</td>
<td>1.9mm</td>
<td>0.283</td>
<td>0.143</td>
</tr>
</tbody>
</table>

Table 2. Geometric parameters for Lego™ roughness used in wind tunnel

<table>
<thead>
<tr>
<th>Surface</th>
<th>Lego™ elements</th>
<th>Lego™ board</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter</td>
<td>$z_0$ (mm)</td>
<td>$d$ (mm)</td>
</tr>
<tr>
<td>Rule of thumb</td>
<td>0.96</td>
<td>6.72</td>
</tr>
<tr>
<td>Lettau (1969)</td>
<td>0.42</td>
<td></td>
</tr>
<tr>
<td>Counihan (1971)</td>
<td>2.56</td>
<td>0.54</td>
</tr>
<tr>
<td>Macdonald (1998)</td>
<td>1.52</td>
<td>1.58</td>
</tr>
</tbody>
</table>

Table 3. Log law parameters derived from surface form for roughness types.

Table 3 shows that Lettau’s (1969) theory gives relatively low $z_0$ values for the Lego™ elements in comparison to the other theories presented. This may be due to Lettau’s (1969) formula (equation 13) being derived from results Kutzbach (1969) who used cylindrical bushel basket as roughness elements which would exert less drag on the flow than the rectangular block shape of the Lego™ elements. Therefore Lettau’s (1969) theory is more applicable to the Lego™ board surface protrusions as these are a cylindrical shape. Lettau (1969) also discusses that below a certain threshold areal density the underlying roughness (Lego™ baseboard in this experiment’s case) is the dominating roughness.
Counihan’s (1971) equations describe the results obtained in wind tunnel experiments using Lego™ elements on a Lego™ base board and so has specific application to the current experiment. However the $\lambda_p$ values for the Lego™ elements for this experiment are outside the limits chosen by Counihan (1971) of $0.1 < \lambda_p < 0.25$ for equation 14a so Grimmond and Ork’s (1999) curve fit of Counihan’s (1971) results is used (equation 14c).

The coefficients used for Macdonald et al. (1998) are, $C_D = 1.2$ for standard 2x1 Lego™ block, $\beta = 1.32$ for Lego™ elements and $\beta = 0.8$ for Lego™ board protrusions. These are calculated (ESDU, 1989) with expected turbulent intensities, velocity profiles and length scales as found in previous experiments on this surface in this wind tunnel (Pascheke, personal communication).

The ‘rule of thumb’, Counihan (1971) and Macdonald et al. (1998) results do not show good agreement for the Lego™ elements $z_0$ ($0.96 \text{mm} < z_0 < 2.56 \text{mm}$) or $d_1$ ($0.54 \text{mm} < d_1 < 1.58 \text{mm}$). In the case of Counihan (1971) the low $\lambda_p$, $\lambda_F$ values for the Lego™ elements are outside the experimental results from which Counihan’s (1971) equation is based on. The ‘rule of thumb’ is based on height alone, does not consider the densities $\lambda_p$, $\lambda_F$ and has coefficients based on mean values for land surfaces. Thus as such a low $\lambda_p$, $\lambda_F$ values are not typical of most surfaces (Grimmond and Oke, 1999) the ‘rule of thumb’ method is considered to provide an overestimate of $d$. Macdonald et al. (1998) theory is considered the most applicable to this Lego™ element surface as it is derived from fundamental principles and has correction factors for the many different aspects that could affect $z_0$ and $d$ such as velocity profile, turbulence and rounded edges. However because the wind tunnel elements work in conjunction with the spires at the start of the wind tunnel the values of $z_{01}$ and $d_1$ are somewhat influenced by the spire setup which cannot be accounted for in these methods.

### 4.1.2 2D bar type roughness

<table>
<thead>
<tr>
<th>Case</th>
<th>$z_{01}/W_x$</th>
<th>$d_2$ (from Leonardi et al. (2003)(mm))</th>
<th>$z_{02}$ (from Kader (1977))</th>
<th>Macdonald et al.(1998)(mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$d_2$</td>
</tr>
<tr>
<td>R1</td>
<td>1</td>
<td>11.7</td>
<td>1.0</td>
<td>10.7</td>
</tr>
<tr>
<td>R2</td>
<td>0.25</td>
<td>7.1</td>
<td>3.8</td>
<td>5.1</td>
</tr>
</tbody>
</table>

*Table 4. Downstream surface roughness parameters. 1 quoted in Raupach et al. 1991.*
There is excellent agreement between the above theories for R1, but for R2 there are slightly smaller values of $z_{02}$ and $d_2$ predicted by Macdonald et al. (1998) compared to Leonardi et al. (2003) and Kader (1977). It is also noted that due to the small cross sectional area of the wind tunnel the blockage factor ($\Phi$) for these element sizes is 6.9%, which is over the 5% VDI guideline. Streamwise velocity measurements are made to test what effect this has on windspeed at a reference height.

Using Macdonald et al. (1998) theory the change of surface roughness from Lego™ to R1 should have the effect of a modest decrease in surface roughness (with $M = -0.42$ (rough to smooth)) but large increase of displacement height ($d_2 = 6.8d_1$). In comparison the change of surface roughness from Lego™ to R2 should result in an increase in roughness length ($M=0.69$ (smooth to rough)) and smaller increase in displacement height ($d_2 = 3.2d_1$).

### 4.2 Profiles above upstream Lego™ roughness

#### 4.2.1 Introduction

The location of profile measurements over the Lego™ surface roughness are shown in Appendix 1. The results of these measurements are shown in Figure 12. Many profiles were taken but due to large changes in temperature ($\Delta T > +1^\circ C$) during some measurements there were errors that were considered too large (>5%) to allow a good comparison with other profiles and so these were not included, but are displayed in Appendix 2.
The normalised wind velocity \( \frac{u}{u_{\text{pref}}} \) at reference height \( z = 178 \text{mm} \) would be expected to be close to 1 as this is the height of the pitot tube. However this does not occur in this experiment (Figure 12). This may be due to a number of reasons, for example the reference pitot tube is located downwind and at a different \( y \) location relative to the hot wire and so any pressure gradient in the wind tunnel may have a consistent effect of relatively low hot wire velocities. There may also be horizontal variations (in \( y \)) that were not tested due to difficulties in equipment arrangement. Differing alignments of pitot tube, calibrating pitot tube or hot wire could cause lower velocities to be recorded as any flow approach angle other than perpendicular to the tube would result in a lower windspeed as shown in section 3.4.4. The lower velocity compared to the reference tube is a consistent feature of every profile taken during the experiment and it is unlikely that alignment is the main cause of these errors. The lower velocities recorded do not affect the conclusions of this experiment as long as there is not large velocity variation with fetch at the reference height over the test section. This was tested (Appendix 3) and found to be a variation of 1.5% which is within the error bounds for velocity measurements (3%) and so not significant.
4.2.2 Upwind boundary layer structure

Boundary layer height

The BL height can be taken as 99% of the free stream velocity (Cheng and Castro, 2000; Kaimal and Finnigan, 1994) although it is not clear from these profiles what the free stream velocity is as there does not appear to be any region where the velocity is constant with height. The concept of free stream velocity implies the influence of the surface is negligible and so in a atmospheric boundary layer $\overline{u'w'}$ would be expected to approach 0 as influence of the ground decreases (Garratt, 1994), However one feature that is not characteristic of an atmospheric boundary layer is that above $z = 140$ mm there are positive values of normalised shear stress (Figure 13) which are due to the influence of the wind tunnel roof which is situated at a height of 230 mm. The boundary layer height estimation will not affect the conclusions of this experiment as the effect of the roughness change (as shown by the theories of IBL height growth in section 2.2.2) will be mainly in the bottom part of the profile for the fetch range of this experiment. The velocity profile does however start to approach a constant value at $z \approx 100$ mm, which will be taken as the height to which this wind tunnels wind profile approximates an atmospheric boundary layer.

Figure 13. (a) Normalised shear stress normalised against $u_{\text{pref}}^2$ (b) shear stress profiles normalised against friction velocity as calculated from the 10% shear stress layer (IS).
Roughness sublayer

The roughness sublayer (RS) can be considered as the region influenced directly by the elements (Garratt, 1994). Over this Lego™ surface the profiles of velocity (Figure 12a), turbulent intensity (Figure 12b) and normalised shear stress (Figure 13b) vary significantly with fetch $x$ around an element up until approximately $2z_H$, which is taken as the RS top. Within the canopy layer there is a large variation of velocity and turbulent intensity (Figure 12). This spatial inhomogeneity is due to the changing location of the HW probe in relation to the elements and consequent measurements of different parts of the wake flow from the roughness elements as found by (Raupach et al., 1980). For example the $x = 1202$ mm profile is directly behind an element and so has almost constant velocity until above $z_H$ due to sheltering, then above this there is strong wind shear and therefore strong shear production of TKE and a resulting high turbulence intensity (equation 20,21) in the wake flow immediately behind the element (turbulent intensity = 0.52 for $x = 1202$mm at $z = 12$mm, Figure 12b) as found by Roth (2000). The greater the fetch after the upstream roughness element the greater the average velocity in the canopy layer and the lower the average turbulent intensity. This is due to less wind shear and corresponding lower turbulent intensity. The shear stress decreases at the top of the canopy layer ($z_H$) due to the influence of the surface. This is supported by the results of Raupach et al. (1980), Antonia and Luxton (1971). Normalisation of the stress profiles against $u^*$ shows that the data collapses into one line, with a shape in good agreement with Raupach et al. (1980) and Pendergrass and Arya (1984) although the latter experiment in particular has a much deeper constant flux ($\sim 10\%$ stress) layer. This may be due to the much larger wind tunnel and subsequent larger upwind fetch (8m) to allow this layer to develop.

The Inertial sublayer

The inertial sublayer is conventionally taken as the region of constant stress to within 10% (Oke, 1987). Above the RS a 10 % variation extends from 23mm to 32mm ($\sim 2-3z_H$ as found by Raupach et al. (1991) in a review of laboratory and field experiments) in both the shear stress profiles taken. It is also noted that velocity and turbulence intensity profiles show the most consistency with fetch in the $2z_H$ to $3z_H$ height range in agreement with the assumptions of horizontal homogeneity implicit in the log law derivation (section 2.1). $u^*$ (IS) values taken from averaging the shear stress measurements within this range are calculated (Table 5) and used to fit a log law and thus derive $z_0$ and $d$. One consideration is that this constant stress layer is not very deep and only 3 measurements per profile were taken in this region. This shallowness could be due to the way in which the BL was formed artificially with insufficient
fetch to allow this layer to deepen. However this may be appropriate to a real boundary layer as there is rarely enough fetch for an equilibrium layer to form due to the heterogeneity of real surfaces. As stated by Roth (2000) in urban areas very little is known about the IS as it is often out of the range of meteorological measurement towers and due to the often large vertical extent of the RS may be very small if it exists at all. For comparison the velocity profiles are fitted for this range using an iterative process (in Curvexpert software) to give values of $z_0$, $u^*$ and $d$ independently of the shear stress measurements.

<table>
<thead>
<tr>
<th>$x$ (mm)</th>
<th>$u^*/u_{pref}$</th>
<th>$z_0$ (mm)</th>
<th>$d_1$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average of profiles fit using $u^*$ (IS)</td>
<td>0.049 ±0.005</td>
<td>0.08±0.06</td>
<td>11.5±2.1</td>
</tr>
<tr>
<td>Average of profiles fit using $u^*$ (RS)</td>
<td>0.052 ±0.006</td>
<td>0.14±0.05</td>
<td>7.5±1.9</td>
</tr>
<tr>
<td>Average (best log fit in IS for all parameters)</td>
<td>0.051 ±0.006</td>
<td>0.13</td>
<td>9.9</td>
</tr>
</tbody>
</table>

Table 5. $u^*/u_{pref}$, $z_0$ and $d$ values calculated from log fits using $u^*$ (IS), $u^*$ (RS) and from best log fitting all parameters.

As the IS as determined by shear stress 10 % layer only includes 3 measurement points for $x = 920, 946$mm and only 2 points for $x = 955, 1051, 1128, 1202$ mm it is difficult to accurately determine values of $z_0$ and $d$. However all the above methods give $u^*$ values that are consistent within the stated error margins. $d_1$ values greater than $11.5$ mm are physically meaningless (as they are above the element height) unless they are due to the lifting effect of the flow by the inlet spires, which provide a blockage to the flow at low levels and a flared gap that increases towards the tunnel roof (Figure 8). These $d_1$ values obtained also appear to be much larger than those predicted by the morphometric methods. These methods (section 2.2.4) are derived from the results of field experiments (e.g. Counihan, 1971; Lettau, 1969) and theoretical considerations (e.g. Macdonald et al. (1998)), usually requiring that the boundary layer is naturally formed and therefore do not account for the artificial generation used in this experiment. In the IS height the turbulent intensity is high ($\approx 0.2$), with the error corresponding to an underestimate of shear stress compared to the true values. The true shear stress values would therefore be higher which would consequently have the effect of reducing $d_1$. Cheng and Castro (2002) also found that the displacement height using a best curve fit in the IS for a sparsely spaced 2D bar type roughness with $z_H/W_x = 0.125$ was larger than the element height. The solution proposed by Cheng and Castro (2002) was to force the displacement height to zero arguing that this would not affect the conclusions of their
experiment. The fit of \( u^* \) (IS) and the corresponding \( z_0 \) and \( d_1 \) values is shown in comparison with the average wind profile in Appendix 4.

The Roughness Reynolds number (equation 18) of this flow using \( u^* \) (IS) and corresponding log fit value of \( z_0 \) is \( \text{Re}_* = 2.3 \) corresponding to a non turbulent flow as described by Raupach et al, 1991. However as stated above \( d_1 \) is unrealistically large, leading to a small \( z_0 \) value. In contrast when the value of \( z_0 \) calculated using the morphometric method of Macdonald et al. (1998) is used the Reynolds number is \( \text{Re}_* = 43.3 \) which corresponds to turbulent flow (Raupach et al. 1991)

An average of \( \bar{u}'w' \) over the RS (not including the canopy layer) was also used to calculate \( u^*(\text{RS}) \) (as in Cheng and Castro, 2002) (Table 5), although there is a lack of sufficient profiles to obtain a good spatial average. However \( u^*(\text{RS}) \) values taken from \( \bar{u}'w' \) measurements in the RS are not representative as the turbulence within this layer is distinctly organised due to the influence of the element geometry, and part of momentum flux is non turbulent (Wieringa, 1993). Also as the wind flow is horizontally inhomogeneous within this region, so representative \( u^* \) values will be difficult to obtain except by extensive measurements in order to obtain a good spatial average. However in field measurements it is most likely that profile measurements are being taken in the RS and this is more likely over very rough urban surface where the IS is usually out of the height range of all but the tallest masts and may not even exist at all over such heterogeneous surfaces.

<table>
<thead>
<tr>
<th>Reference</th>
<th>( \delta/z_0 )</th>
<th>( u^* ) (IS)/upref</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pendergrass and Arya (1984) 3D array of blocks</td>
<td>1150</td>
<td>0.054</td>
</tr>
<tr>
<td>Cheng and Castro (2002)</td>
<td>104</td>
<td>0.070</td>
</tr>
<tr>
<td>Counihan (1975)(^1)</td>
<td>500-1500</td>
<td>0.043-0.06</td>
</tr>
<tr>
<td>Present experiment</td>
<td>1000±300</td>
<td>0.049</td>
</tr>
</tbody>
</table>

Table 6. Comparison table of \( u^* \) (IS)/upref values. 1. A review of urban atmospheric data

Table 6 gives a summary of the \( u^* \) (IS)/upref results found by different authors. Cheng and Castro (2002) have a particularly small ratio \( \delta/z_0 \), which is due to the forcing of \( d_1 \) to zero which may result in a particularly large \( z_0 \) value if a significant non-zero displacement height does exist for their surface. Other authors find similar values (within ± 0.005 error limits) of \( u^* \) (IS)/ upref although no indication is given of the uncertainty of these measurements, which
may be considerable (>10%) for measurements of $u'w'$ in the IS. Counihan’s (1975) review also indicates that the current study has values typical of urban areas. The concern of the use of $u_{\text{ref}}$ as a normalising factor for comparisons is that this pitot tube is located downstream of the hot wire and pressure differences may cause the wind tunnel speed to increase towards the back of the wind tunnel, leading to the normalised velocity at reference height not reaching unity as shown in Figure 12a.

### 4.2.3 Turbulence over Lego™ surface

In the RS the turbulent intensity is spatially inhomogeneous as described in section 4.2.2 and Figure 12b. Because of the influence of the individual elements it is difficult to obtain a spatial mean for the RS. However in the IS the turbulent intensity is relatively constant in the $x$ direction as shown by the good agreement between profiles in Figure 12b.

![Figure 14. Turbulent intensity components, $\sigma_w/U$, $\sigma_w/U$ and $\sigma_w/\sigma_u$.](image)

A $u$, $w$ component turbulence intensity profile is given in Figure 14. This reveals that the $w$ component turbulent intensity is always less than the $u$ component although it follows a similar pattern of increasing closer to the surface until the top of the canopy layer ($z_H$), and below this where it is constant or decreasing in intensity. In the RS the spatial inhomogeneity of the flow causes a large vertical variation of turbulent intensity increasing rapidly to a peak.
at $z_H$ followed by a decrease towards the surface. However more profiles would have to be
taken to get a good picture of the spatial distribution of turbulent intensity in the RS. This is
evident by the large difference in $\sigma_w/\sigma_u$ ratios in this layer as opposed to the good agreement
of these in the IS and above. The ratio of $\sigma_w/\sigma_u$ is larger than the VDI (2000) guideline except
for the 946mm case at less than the element height $z_H = 11.5 \text{ mm} = 23\text{ m}$. Because these ratios
are approximate and are derived from field experiments that only have a limited height ($z = 0
- 50\text{ m}$) range they are only appropriate for heights close to the ground. As the height from the
surface increases it would be expected that due to the decreasing influence of the ground
surface the turbulent intensity components would approach a 1:1:1 ratio. There is relatively
small vertical variation in the ratios of each turbulent intensity component within the region
11.5-19 mm as found by Roth (2000) in his review of turbulence over cities. It must be noted
that the turbulence values for the $u$ component are <30 % and are subject to additional errors
as described in the section 3.4.5 and Appendix 5.

![Figure 15. Turbulent intensity components, $\sigma_u/U$, $\sigma_v/U$ and $\sigma_v/\sigma_u$.](b)

Figure 15 shows that the ratio of $v$ to $u$ components is in the correct range within 1 - 1.5$z_H$
(equivalently 23m - 32m in full scale), which is the correct range when compared to
atmospheric measurements. Above 85.2mm this ratio becomes consistently greater than 1
which is not a feature of atmospheric turbulence. This effect is probably due to the way
turbulence is generated by spires in the wind tunnel, as the vertical arrangement of the spires may correspond to the generation of excessive v component turbulent intensity. The ratio $\sigma_v/\sigma_u$ for each of the profiles taken shows good agreement in the IS and above which is in agreement with the horizontal homogeneity of this layer. In the RS the ratio is different with the greatest differences occurring at $z_{H}$, which is a result of the strong shear layer created as air flows over the element top.

4.2.4 Turbulence spectra

VDI (2000) stipulates that turbulent spectra as described in Table 1 are valid for heights of 10m or more above the mean roughness element height $z_H$. Thus in full scale $z > 33m$ for Lego™ element roughness or equivalently $z > 16.5$ mm in terms of local scale. However although not stated the displacement height should be accounted for as this equivalent to raising the level of the surface, so $z-d < 16.5$mm. As the displacement height over the Lego™ elements $\approx 11$mm, then spectra are taken at $z = 28.5$mm. Using the reduced frequency $f(z-d)/u$ allows the spectra to be a good method of comparison to atmospheric turbulence as takes the wind tunnel scale into account. The turbulence spectra are however dependent upon inputting the correct height minus the displacement height. The u component energy spectra shows good agreement, while the v and w components have too much energy at all the observed frequencies but do have the correct shape (Figure 16). This excessive energy in v and w components may be due to the way turbulence is generated using spires.

![Figure 16. Normalised spectral energy density distributions at a height of 28.5mm over Lego™ surface. Atmospheric surface layer spectra are shown for comparison (Kaimal et al., 1972)](image)
4.3 Profiles over R1 roughness type

Normalised wind profiles show differences between different fetches (Figure 17), e.g. at the reference height (z=178mm) these differences are large (~5%) but show no pattern with fetch. Therefore these differences are most likely due to errors incurred during measurement or calibration. In comparison to the Lego™ profiles, where profiles were rejected if the temperature changed significantly during a profile, the constraints of time and the occurrence of exceptionally hot weather during the measurement days over R1 meant that large temperature changes (+1°C) did occur. Because the main points of interest were considered to lie in the bottom part of the profile to minimise error the profiles were taken from the bottom upwards and therefore shortly after a calibration correction temperature reading. However a 1°C change should only contribute a 2% error and so additional factors must have been influencing the readings. These could include the blockage factor (Φ) increase of 6.25%, causing an acceleration of flow speed due to the decrease in cross-sectional area over the bar roughness. This was assessed by a measuring windspeed at the reference height of z = 178mm and was determined to be 2.5% speed increase over the x = 1032 - 1190mm fetch (Appendix 3). There may also be additional errors from calibration and due to hot wire and two pitot tubes alignment changing in-between profiles.

Figure 17. Wind profiles after change in roughness from Lego™ to R1 type roughness including upwind velocity profile for comparison.
4.3.1 Initial flow disturbance

Features within the bottom of the profile include the relatively high velocities in the range $z = 18.2 – 32\text{mm}$ over first bar roughness ($x = 1038\text{mm}$) compared to the upstream profile (Figure 17). The estimation of the lower limit of this acceleration is set by the lowest measurement possible and the upper limit is the height of re-mergence with the upstream profile although this is only approximate due to the large scatter of data. The basic elements of this flow feature are shown in Figure 18.

The acceleration of the flow over bar 1 is due to streamlines converging, creating a jet as shown in Figure 18. This feature is supported by the positive values of normalised shear stress (Figure 19) at this point, showing that the locally the momentum of the wind at 18.2$\text{mm}$ is not acting upwards rather than downwards on the surface as the airflow is forced up over the bar by the pressure increase on the bar’s upstream face. Because of this upward motion the shear stress is positive and therefore TKE decreases compared to upstream values due the shear production becoming locally very small/ negative. However although the results indicates shear stress loss it is unlikely as this signifies a counter gradient flux. This may be due to the error associated with the velocity gradient term at this point.

Compared to the upwind Lego™ profile, after the initial faster flow over the first bar and canyon, profiles at greater fetches (i.e. after bar 2) show slower velocities up to a height of $z = 36\text{mm}$. The scatter of data does however make it difficult to draw any conclusions about if

![Image of flow disturbance](adapted from Oke, 1987)

Figure 18. Flow disturbance caused by roughness change (adapted from Oke, 1987).
this has any pattern with increasing fetch. The shear stress pattern in Figure 19 also does not appear to vary above \( z = 36 \text{mm} \) with any pattern corresponding to the wavelength of the bar spacing. This is one indication of the extent of the RS. Below \( z = 36 \text{mm} \) the shear stress develops into a regular oscillating pattern.

![Change in roughness graph](image)

**Figure 19.** Normalised shear stress variation with fetch including upstream Lego™ values for comparison.

### 4.3.2 Shear stress

Wieringra’s (1993) formula of the fetch needed to obtain equilibrium flow (equation 11) up to the height of the RS \( (3z_{th}) \) using morphometric \( z_0, d_2 \) values from Macdonald et al. (2000) is \( x_F = 3030 \text{mm} \) which is far larger than the fetch available in this experiment \( (160 \text{mm}) \). Even if the RS was only \( 2z_{th} \) deep Wieringra’s (1993) theory predicts a fetch of \( x_F = 1440 \text{mm} \). Cheng and Castro (2002) and Roth (2000) both comment that because in practice there are no field studies over urban areas with large enough areas of homogeneous surface roughness it is not known how well Wieringra’s (1993) formula performs in practice for such a rough surface. Cheng and Castro (2002) used a method based on percentages whereby the height of the equilibrium layer is that at which the velocity attains 101%, 105% or 110% of the velocity at that height if the surface roughness was identical to that of the downstream (i.e. no roughness change). This method was possible in Cheng and Castro’s (2002) experiment as profiles were taken of both their upstream and downstream surfaces independently before installing a
roughness change. Compared to these methods Wieringra’s (1993) formula estimates very low equilibrium layer heights (Cheng and Castro, 2002). However in this study setting up the whole wind tunnel length with uniform downstream roughness bars was not possible as this would require developing a new spire setup to work with this roughness.

\[
\frac{u'w'}{u_{\text{pref}}^2}
\]

Because of the fetch required for equilibrium there is not expected to be any constant flux layer above the RS, which is confirmed by Figure 20. However by applying the definition for the IS, i.e. a 10% variation in shear stress (Taken here from above 2z_H), there does appear to be a layer equal in depth to the IS over the Lego™ surface. However in the available fetch there should not be any constant fetch equilibrium layer above 2z_H (Wieringra, 1993). It is the presence of a peak in shear stress in this region and the use of the 10% variation in shear stress definition of the IS that leads this ‘constant’ stress layer being observed. It is necessary to use the definition that a 10% variation in shear stress approximates a constant flux layer (Oke, 1987) as shear stress measurements at this height are subject to large errors (Tutu and Chevray, 1975) and so some allowance for this is needed. This pseudo-constant stress layer allows calculation of \( u* \) values although this is not strictly valid because of the assumption of equilibrium in the derivation of the relationship between the covariance and \( u* \) (section 2.1). \( u* \) does however have direct application for use as a scaling factor. The overall trend of the \( u* \)

![Figure 20. Normalised Shear stress profiles over R1 type roughness. (a) over bar profiles. (b) over canyon profiles.](image-url)
values over the fetch range is a small increase from $u_* = 0.43 \text{ ms}^{-1}$ at $x=1038\text{mm}$ to $u_* = 0.465\text{ms}^{-1}$ at $x = 1190\text{mm}$ (Figure 21). The pattern of points with this increase is very scattered with one very large increase at $x = 1128.5\text{mm}$. The small size of this increase, the small number of measurements and scatter of the points puts doubt on the conclusion that there is a significant increase. Because $u_*$ is dependent on windspeed and surface roughness, by keeping the windspeed constant for this study, the lack of significant change in $u_*$ indicates a negligible change in roughness as supported by the morphometric analysis results in section 4.1.1 (Table 3,4)

![Change in surface roughness](image)

Figure 21. $u_*$ values variation with fetch as determined from 10% variation of stress layer and from peak of shear stress.

There is also almost no change in the magnitude of the normalised shear stress peak between the upwind and downwind surfaces for the 1st 4 rows of R1 ($u'w'/u_{pref}^2 = -0.0027$ and -0.0028 respectively), and only a small increase at $x=1227.5\text{m}$ to $u'w'/u_{pref}^2 = -0.0030$. The peak by the end of the experimental fetch does appear to be higher ($z = 19.6\text{mm}$ for upstream, $z = 32\text{mm}$ above the first bar of R1 to $z = 40.9\text{mm}$ over the 7th bar). This may be an indication of the significant displacement height change predicted by the morphometric analysis (Table 3, 4) and surface level increase between the two roughnesses. This displacement height change is not however supported by the values of $d$ from profile measurements as shown in Table 5.
The feature of a peak in shear stress increasing in height with increasing fetch x after the change in roughness is supported by the results of Antonia and Luxton (1971).

By separation of the $u'w'$ results into above bar and above canyon fetches a few features are apparent. Although both groups achieve similar peak shear stress magnitudes the over canyon results show higher overall values in the RS (Table 7). This is due to the influence of the surface being further away and movement of eddies in and out of the canyon.

<table>
<thead>
<tr>
<th>Location</th>
<th>Average z (mm) location of peak $u'w'/u_{\text{pref}}^2$</th>
<th>Average $u'w'/u_{\text{pref}}^2$ in RS $(z\geq36\text{mm})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Over canyon</td>
<td>27.3±5.5mm</td>
<td>-0.00253±0.00015</td>
</tr>
<tr>
<td>Over bar</td>
<td>32.3±6.2mm</td>
<td>-0.00210±0.00035</td>
</tr>
</tbody>
</table>

**Table 7. Differences between over bar and over canyon normalised shear stress**

### 4.3.3 Turbulence response

The u component turbulent intensity shows that the peak at height $z=18.2\text{mm}$ occurs at fetch $x=1051\text{mm}$ (Figure 22). As the height increases the peak of the intensity shifts downstream. The amplitude of this peak decreases at higher levels being negligible at $z=36\text{mm}$. This is another indicator that (within the available fetch) the new surface does not exert an effect on the flow above this level as above this the TI shows either no change or a slight decrease in comparison to the upstream values. The gradual decrease of turbulent intensity at higher levels (for example 85.3mm) is a characteristic of the wind tunnel as the generation of turbulence at these levels is due to the spires and so this decreases gradually with distance from the tunnel inlet. This is confirmed by the fetch profile in Appendix 3, and is identical in magnitude in both R1 and R2 profiles at the reference level $z=178\text{mm}$. 


One reason for why the peak turbulent intensity doesn’t occur over the first bar can be found by examination of the turbulent kinetic energy (TKE) budget. Near the surface the shear production term usually makes a large contribution to the TKE budget and therefore the turbulent intensity (equation 22) is due to relatively large $u'w'$ values and strong wind shear. However over the first bar there is positive shear stress and accelerated flow due to convergence of flow lines. This positive shear stress combined with the decreased wind shear at 18.2 mm (the bottom of the measurement range) leads to shear loss in the TKE budget. However this counter gradient flux is most likely to be due to error in the velocity gradient measurements as it is not physically meaningful to have a shear loss. It is likely that the high turbulent intensity at $x = 1051$ mm (1st canyon) is due to the divergence of streamlines (Figure 19) reducing velocity in the wake region (Figure 22) due to the decrease in pressure in comparison to the upstream face of the bar leading to higher turbulent intensities at this point.

Because the R1 surface bars are closely spaced the flow over these elements is predicted by the theories of Oke (1987) to be a skimming regime with a roughness length that is only slightly different to the upstream Lego™ surface (see morphometric results, Table 3,4). Thus it is likely that the turbulent intensities over R1 should not be much different in magnitude to

Figure 22. Turbulent intensity u component over R1 type roughness including upstream values for comparison.
upstream. This is indicated as after the peak disturbance the turbulent intensity within the RS ($z \leq 36\text{mm}$) decreases approaching values found upstream (Figure 22). This decrease in turbulent intensity is an indicator that this surface is not rougher as a rougher surface would provide a consistently higher turbulent intensity close to the surface via enhanced TKE production.

**Figure 23. w component turbulent intensity including upstream values for comparison**

Due to the influence of the surface the w component of turbulent intensity is smaller than the u component. This surface influence is visible in Figure 23 with higher turbulent intensity over the bars and comparatively lower turbulent intensity over the canyons. This influence appears to extend up to a height of $z = 23\text{mm}$ where the amplitude of this effect becomes negligible. The w component follows a similar pattern to the u component with a peak at $1051\text{mm}$, with the fastest decreases occurring at the low heights (e.g. $z = 18.2\text{mm}$). Over bars 5,6 the peak of turbulent intensity occurs at higher levels, for example $z = 19.6$ at bar 3, $z = 21\text{mm}$ at bar 4 and $z = 25\text{mm}$ at bars 5,6 and canyon 6. However results close to the end of this pattern are close to the end of the roughness and so may be adversely affected by the approaching change in blockage coefficient.
4.4 R2 roughness type

4.4.1 Velocity and shear stress

Wind profiles over R2 show much more consistency higher in the profile due to better minimising of errors during these measurements. This was achieved by more frequent temperature and pressure measurements as well as clamping of pitot tubes to minimise movement (and therefore alignment errors) of equipment during measurement and calibration. Also a period of cloudy weather also helped to reduce daytime temperature fluctuations during this period. This resulted in a much better agreement of profiles (Figure 24), showing clearly some of the features that were not clear due to result scatter in R1 results.

![Graph showing wind profiles after change in roughness from Lego™ to R2 type roughness including upwind velocity profile for comparison.](image)

Figure 24. Wind profiles after change in roughness from Lego™ to R2 type roughness including upwind velocity profile for comparison.

The flow over the 1\textsuperscript{st} bar shows the same acceleration jet and corresponding positive shear stress values as in R1. The profile at x = 1070mm also shows faster windspeeds in comparison to the other profiles. It is the solid obstacle of the bar that forces the flow upwards and to accelerate over the 1\textsuperscript{st} bar creating a localised shear stress undershoot with positive shear stress values (e.g. $\frac{u''w''}{u_{\text{pref}}^2} = 0.001$ at $z = 18.2\text{mm}$) (Figure 25) as opposed to the expected overshoot for this situation (see section 2.2.5). This however is a localised effect as this surface should according to the morphometric analysis exert an increased drag due to an increase in roughness and should therefore decelerate the flow. In the range $2z_H - 3z_H$ there is
evidence of the flow decelerating after this initial acceleration over the 1st bar. The greater the fetch the slower the velocity of the profile in this height range.

![Graph](image)

**Figure 25.** Normalised shear stress values for a change of roughness from Lego™ to R2 type roughness. Includes upstream roughness values for comparison purposes.

After the initial disturbance (x = 1038 - 1070mm) the shear stress increases in accordance with the deceleration signifying an increased roughness compared to upstream (Figure 25). Figure 25 also shows the relatively low shear stress measurements in the x = 1038mm profile between heights zH to 3zH corresponding to the existence of accelerated airflow over the first bar. The flow closest to the surface adjusts in a periodic manner of equal wavelength to the spacing between bars, with relatively low shear stress over a bar and high shear stress over the canyons. This is similar to that measured over R1, and again the amplitude of this disturbance extends up to a height of 40.9mm ~ 3zH. At this level there is an overall increasing magnitude trend in shear stress beginning at x = 1102mm, in accordance with the fetch required for the increased roughness to begin influencing the flow at this height. At heights z = 18.2 – 36 mm after the increase in stress there appears to be a stabilisation of the oscillating pattern as values at x = 1200mm are the same as those at x = 1290mm although measurements at greater fetches are required to confirm that this pattern has indeed become repetitive in terms of amplitude of fluctuations at these heights. Cheng and Castro (2002) did find that a pattern of
high low did become regular at some distance after the roughness change with a pattern the same as that of established flow over a large fetch of such roughness.

![Figure 26. Normalised shear stress profiles over R2 type roughness. (a) over bar profiles. (b) over canyon profiles.](image)

Most of the shear stress change in the $z = 25 - 36$ mm range occurs between $x = 1100$ mm and $x = 1165$ mm as is also evident from Figure 26, where the peak of normalised shear stress over bars makes a large jump from $-\frac{u' w'}{u_{pref}^2} = 0.0025$ at $x = 1102$ mm to $-\frac{u' w'}{u_{pref}^2} = 0.004$ at $x = 1166$ mm. As the fetch increases the shear stress in this range increases until measurements at $x = 1197$ mm and $x = 1260$ mm both have values 0.0005 higher than over bar profiles. This difference was not evident over R1 roughness, the difference being that there is greater fetch between each bar. This means that measurements in the middle of each canyon are within the wake interference flow so flow lines deflect downwards slightly into the canopy layer rather than skimming over the top. This downward angled flow pattern has the overall effect of increased shear stress in the flow immediately over the canyon. There is also a less sharp peak over the canyons due to less influence from the surface. However the error of such high shear stress measurements is large (10%). The reason why this larger peak in shear stress for over canyon profiles is more noticeable over R2 than R1 is because of the larger spacing between elements and therefore greater fetch available between bars and relatively less error in probe positioning in relation to the center of the canyons. Over the first canyon there is no peak in
the shear stress within the measurement height range, while at greater fetches there is a peak that appears to increase in height with increasing fetch.

Figure 27. $u^*$ values variation with fetch as determined from 10% variation of stress layer and prom peak of shear stress.

Figure 27 shows the development of $u^*$ as measured from shear stress measurements in a 10% layer above $2z_H$. Compared to the R1 there is a bigger change from $u^* = 0.45\text{ms}^{-1}$ over the 1st bar to $u^* = 0.57\text{ms}^{-1}$ over the 4th canyon. This change is significant within the indicated error bounds.

4.4.2 Turbulent Intensity

Initially the $u$ component turbulent intensity shows a similar form to R1 with almost identical values over the first bar (Figure 28). This shows that this initial flow disturbance is not dependent on the form of the downstream roughness but rather a feature due to the shape/height of the 1st bar. However by the middle of the 1st canyon the turbulent intensity at $z = 18.2\text{mm}$ has increased at two times the rate of increase over R1. This rate of increase is even larger at heights $z = 19.6, 21\text{mm}$, and the rate of increase decreasing at higher levels until $z = 52.2 \text{mm}$ where there is negligible increase compared to the turbulent intensity over the 1st bar. After this initial increase the turbulent intensity at $z = 18.2\text{mm}$ stays at an almost constant level of 0.375 until the end of measurement fetch. This consistently higher value is an indication of a rougher surface, rather than the peak and subsequent decrease observed at the
same height over R1. Compared to the downstream values at $z = 19.6\text{mm}$ there is a jump in turbulent intensity from 0.265 over the 1st bar to a consistent 0.355 over the rest of the measurement fetch. This could be a result of the changing surface level (+1.7mm), but even when this is taken into account by estimating the turbulent intensity values at $z = 19.6 + 1.7 = 21.3\text{mm}$ the increase of turbulent intensity is $+0.06$. There is the displacement height to consider as morphometric analysis of Macdonald et al. (1998) predicts an increase of 3.5mm, although profile measurements over the Lego™ did not support this. The combination of surface level and displacement height change may displace the flow vertically by up to 5.2mm, which gives an equivalent height $z = 19.6 + 5.2 = 24.8\text{mm}$. By estimating from values at $z = 25\text{mm}$ (due to the large errors in turbulent intensity measurement and displacement height uncertainties this assumption is not significant) the turbulent intensity at the end of the measurement length is 0.30, an increase of 0.03 from the upstream value. The above assumptions do however assume that the readjustment of the flow to the new surface at this height has occurred within the available fetch which is not the case as the turbulent intensity is still increasing at this level. An experiment with a longer measurement fetch would be required to confirm if this is occurring.

Figure 28. Turbulent intensity $u$ component over R2 type roughness including upstream values for comparison.
The w component turbulent intensity at height \( z = 18.2 \), 19.6mm (Figure 29) also shows an increase which is twice as large as compared to that observed over R1 (Figure 23). The same periodic pattern as over R1 is observed although the larger spacing between bars makes this more pronounced, with a amplitude between low and high that is approximately four times larger than over R1 at \( z = 18.2 \)mm. The height at which this amplitude becomes negligible is \( z = 23 \)mm in agreement with the R1 roughness.

The turbulent intensity rate of increase of u and w components becomes less and less at higher levels until \( z = 66.8 \)mm where the trend becomes a decreasing one. This is a feature of the wind tunnel turbulent intensity variation with fetch as discussed in section 4.2.3. Another indicator that this is not an effect of the roughness change is that this effect is the same magnitude over both R1 and R2 roughness.

![Figure 29. Turbulent intensity w component over R2 type roughness including upstream values for comparison.](image)

**4.4.3 IBL height.**

The IBL height is only calculated for the R2 surface roughness as the velocity profiles are more consistent than those over R1, and therefore easier to interpret. The results of the shear stress (Figure 25) appear to show that the RS extends up to 3\( z_H \) and the velocity profiles are characteristic of the upwind surface above this height. Thus the equilibrium layer does not extend above the RS and so it is not possible to determine the downwind log law parameters.
$z_{02}$ and $d_2$ by profile measurements. However the $d_2$ and $z_{02}$ values as determined by the morphometric analysis can be used to estimate the IBL height.

![Graph showing IBL height growth](image)

**Figure 30. IBL growth after a change in surface roughness from Lego™ to R2.**

The IBL heights were obtained by measuring height of inflection ($\delta_i^2$) of the downstream influenced wind profile and the upstream influenced flow. The method of using the point of intersection between the upwind and downwind profiles ($\delta_i$) was also used for comparison although its application is not strictly valid as the downstream profile is in the RS and dependent on surface form. Overall as predicted in section 2.2.2 $\delta_i$ gives larger values of IBL height (see Figure 30). It is noted that the error of these measurements is large ($\pm 6$mm) due to curve fitting errors and the difficulty in interpreting the inflection point. The theories of Elliot, 1958 (Equation 7); Wood, 1982 (Equation 9); Panofsky and Dutton, 1984 (Equation 10) are presented using roughness parameters calculated using upstream and downstream $z_0$ parameters obtained using the morphometric analysis of Macdonald et al. (1998)(Figure 30) as well as upstream $z_0$ values obtained from the log profile fit using $u_\ast$(IS). Elliot’s (1958) theory shows the best agreement with the experimental results although the limited fetch
range of experimental results and large errors make it difficult to make any conclusions about the growth at longer fetches. Panofsky and Dutton (1984) show reasonably good agreement with the rate of increase of the experimentally derived IBL height. Wood’s (1982) theory gives a very slow estimation of IBL growth in comparison to the above theories and the results obtained, as found by Savelyev and Taylor (2005) in their review paper. The effect of using $z_0$ from the log law fit using $u^*(I)$ for the upstream profile is also shown in Figure 30, leading to a slightly slower IBL growth rate as compared to that obtained from purely morphometric results.

![Figure 31. IBL growth after a change in surface roughness from Lego™ to R2 including consideration of displacement height change](image)

The displacement height is not considered in any of the theories presented, but as it is a large percentage of the calculated IBL depth the experimental results can be adjusted by taking the surface level as equal to $(d_2 - d_1)$ ($d_2 = 3.5$mm from morphometric analysis of Macdonald et al. 1998). The effect of this is to give a larger IBL depth in relation to the surface, bringing Panofsky and Dutton’s (1984) theory into better agreement with the experimental results (Figure 31).
4.4.4 Shear stress overshoot

The theoretical shear stress overshoot as described by Barlow (personal communication) and Jensen (1978) are calculated using the IBL height predictions of Elliot (1958) as these appear to be closest to the experimental results obtained above. The values of upstream and downstream $z_0$ and $d$ are those predicted by the morphometric analysis of Macdonald et al. (1998), as this means a consistent theory is used for both surfaces. The results of these theories are displayed in Figure 32. Both Jensen (1978) and Barlow (unpublished) predict shear stress overshoot, with the peak of overshoot occurring at 1mm downstream of the start of the roughness change for Jensen (1978) and 8mm downstream for Barlow (unpublished). The value of the peak is not critical as both theories predict infinite shear stress ratio’s at particular IBL depths, for example Barlow (personal communication) asymptotes when $(\delta_i - d_2) = z_{01}$.

![Figure 32. Shear stress overshoot as predicted by the theories of Barlow (unpublished) and Jensen (1978), for a change in roughness of Lego™ to R2 using the values of upstream and downstream $z_0$ and $d$ as calculated using the morphometric analysis of Macdonald et al. (1998) and IBL height values of Elliot (1958).](image-url)
The predictions in Figure 32 do not agree with the results obtained from a 10% variation in shear stress layer above \( z = 2z_H \). However the values of shear stress measured are highly height dependent. The location of a large overshoot over the first bar of R2 is not evident within the height range of this experiment, and it was actually found that for this change in roughness resulted in a decrease of shear stress over this bar due to the acceleration of flow. This is due to using a 2D roughness element and measurements over 3D roughness changes could give different results although this would be difficult unless a larger wind tunnel was used as spatial averaging would be required. The measurement of shear stress overshoot is also likely to depend on the measurement technique used as direct measurements using pressure tapping (Antonia and Luxton, 1971) or drag plates (Bradley, 1968) have clearly revealed overshoot, avoiding the difficulties of above surface shear stress spatial inhomogenities.

5 Conclusions

The first part of the experiment was to create and verify against atmospheric observations a boundary layer in the wind tunnel. The upstream flow was found to be consistent with the log wind law, and turbulent intensity in good agreement with that expected for a rough surface (VDI, 2000). The turbulent energy spectra is in accordance with the results of Kaimal et al.,(1972) in the u component but with too much energy in the w and v components. The RS was found to extend up to \( 2z_H \) and assuming that a 10% variation in shear stress above this is considered constant the IS is found to extend from \( 2z_H \) to \( 3z_H \). From log profile measurements within this height range the log law parameters \( z_0 \) and \( d_1 \) were deduced and found to be much larger than predicted by morphometric analysis methods. This is considered to be a result of the artificial generation of turbulence by spires, and similarly excessive \( d \) values have been reported from using this method in the wind tunnel study of Cheng and Castro, 2002. Also the error due to high turbulence corresponds to an underestimate of shear stress compared to the true values, thus giving artificially high \( d \) values during the curve fitting process. \( u^* \) values were also obtained by using shear stress measurements in the RS and by best fitting all profile parameters simultaneously which gave consistent results within the bounds of error.

Two different changes in surface roughness were considered, both 2D in structure. This surface structure results in a periodic variation of shear stress and w component turbulent intensity with fetch. This periodic variation has wavelength equal to the bar spacing and an amplitude that decreases with height. A commonly observed feature of previous roughness
change experiments is a shear stress overshoot, which is not observed in this experiment. However it is found that the shear stress variation with fetch is highly dependent on the height at which it is measured. Another consideration is the experimental method as almost all previous experiments that have observed this shear overshoot have used direct measurements of momentum flux on the surface by means of drag plates or pressure tapping. However previous experiments have often used roughness changes of much larger magnitude M than studied here and 3D surface morphology, which due to the spatial averaging required over 3D element structures, needs a larger wind tunnel.

The shear stress overshoot was theoretically predicted by two separate theories to be located over the 1st bar of the downstream roughness which due to the particular form of the change in this study actually had a localised effect of reducing the stress over this location due to the presence of a jet. Thus the existence of an overshoot is dependent on the form of the roughness change and may still be a feature of changes to 3D surface roughness. The scale of the wind tunnel also may play a role as to provide a rougher surface the downstream bar roughness height (zH) has to be large (16% of the boundary layer depth).

The upstream surface in this experiment works in combination with the turbulence producing spires and so its roughness cannot be changed without extensive experimentation, the disadvantage being that is actually relatively rough and so it is difficult to create a surface of higher roughness whose elements are not excessively large as a fraction of the boundary layer. Elements that are too large have a large blockage coefficient which has the effect of speeding up the flow in the test section which is undesirable because this is not a feature associated with full scale experiments and therefore makes comparison of results difficult.

The differences between the two downstream roughness was a due to changing the ratio of element height to canyon width ratio, with R1 having a 1:1 ratio and R2 setup to obtain maximum z₀ values with a 1:4 ratio. The effect of these two ratios had a large effect on the turbulent response, with the turbulent intensity over R2 of both u and w components in the RS initially experiencing an increase twice the magnitude of that at the same heights over R1. After this initial turbulent intensity increase a decrease was measured with increasing fetch over R1 suggesting that the initial increase was a localised feature caused by the flow encountering the first bar roughness. In comparison the turbulent intensity at the same levels over the R2 roughness were consistently higher than those over R1 suggesting an increase in
surface roughness compared to the upstream Lego™, as predicted by the morphometric analysis.

Previous work into the effect of the change of surface in surface roughness has revealed that an IBL grows with increasing fetch downwind of the change. Below this IBL the flow is in a transition state, and if enough fetch is available a new equilibrium layer will form. However the airflow above the roughness elements is spatially inhomogeneous due to the influence of the roughness elements. This is the RS and it is necessary for the equilibrium layer to become deeper than this layer before the log law of the wind can be correctly applied due to the assumptions of constant stress and horizontal homogeneity inherent in its derivation. In this study due to the limited amount of fetch available the equilibrium layer did not extend above the RS. However surface parameters $z_0$ and $d$ were calculated by consideration of the surface geometry. This allowed various theories of IBL growth to be compared to those inferred from velocity profile gradients. The results obtained were consistent with the theories of Elliot (1958) within the error bounds. However a larger wind tunnel with greater measurement fetch would be required to confirm if this is the case at longer fetches. Further work could also be done to investigate the effect of a displacement height change on IBL depth as this is not considered by any of the theories used in this study. The displacement height is a large proportion of the IBL depth at small fetches and so will make a difference to the shear stress predictions used in this study that are dependent on IBL height estimation.

The downwind surface is considered to be of urban roughness and as the results of this experiments show that large fetches would be required to obtain an equilibrium layer above the RS it is unlikely that due to the heterogeneity of a typical urban area an equilibrium layer would ever be present. Also the height at which such a layer would occur ($3z_H = 76m$) would make conventional measurements out of reach. Thus the use of wind profiles in urban studies for obtaining wind law parameters is theoretically dubious at it is likely that the wind profile would be highly dependent on location of measurement in relation to the roughness elements.

During the experiment the need for regular temperature and pressure measurements to correct the calibration of the hot wire and pitot tubes was recognised, the result of this is that results over R2 show much better agreement than those over the R1 surface which were taken earlier in the measurement period. However high turbulence (turbulent intensity <0.2) results in large
errors in shear stress, velocity and turbulent intensity. One aspect for future study would be to implement an error correction scheme to minimise these cross wire related errors.
Appendices

Appendix 1. Location of profile measurements over Lego™ surface roughness

Figure 1A. Location of profile measurements over Lego™ surface roughness

Appendix 2. Rejected Lego™ wind profiles.

Figure 2A. Lego™ wind profiles rejected due to large temperature related errors.
Appendix 3. Change in normalisation wind speed with fetch

Figure 3A. Change in normalised velocity with fetch at z=178mm over Lego™ surface roughness.

Figure 3B. Change in normalisation wind speed and turbulent intensity with fetch over change in surface roughness from Lego™ to R1, measured at z=178mm.
Appendix 4. Log law fit using u* (IS) and average velocity profile over Lego™ surface

\[
\begin{align*}
    d_i &= 11.47 \text{ mm} \\
    z_0 &= 0.08 \text{ mm} \\
    u_*/u_{pref} &= 0.049
\end{align*}
\]

Figure 4A. Log law fit using u* (IS) and average velocity profile over Lego™ surface

Appendix 5. Errors in mean velocity and shear stress measurements

<table>
<thead>
<tr>
<th>Measured Turbulent Intensity</th>
<th>% Error in mean velocity $\bar{u}$</th>
<th>% Error in shear stress $u'w'$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>2</td>
<td>-3</td>
</tr>
<tr>
<td>0.2</td>
<td>4</td>
<td>-10</td>
</tr>
<tr>
<td>0.3</td>
<td>7</td>
<td>-25</td>
</tr>
<tr>
<td>0.4</td>
<td>10</td>
<td>-36</td>
</tr>
<tr>
<td>0.5</td>
<td>20</td>
<td>-50</td>
</tr>
</tbody>
</table>

Table 1A. Error estimate for mean velocity and shear stress measurements using cross wire anemometry (Tutu and Chevray, 1975)
References


JØRGENSEN, F. E., (2002). How to measure turbulence with hot wire anemometers – a practical guide. *Dantec Dynamics, P.O. Box 121, Tonsbakken 16-18, DK-2740 Skovlunde, Denmark*.


KUTZBACH, J. E., (1961). Investigations of the modification of wind profiles by artificially controlled surface roughness. University of Wisconsin Department of Meteorology annual report, 71-113


MIYAKE, M., (1965). Transformation of the atmospheric boundary layer over inhomogeneous surfaces, Science Reports 5R-6, University of Washington, Seattle, U.S.A.


