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Guidance Material

Building-Induced Wake Effects at Airports

Working Paper

Report prepared by SLR Consulting Australia Pty Ltd for the Department of Infrastructure and Transport

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Guidance Material for

Building-Induced Wake Effects at Airports

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Executive Summary

SLR Consulting Australia Pty Ltd (SLR) has been commissioned by the Department of Infrastructure and Transport (the Department) to develop suitable **Guidance Material** covering the effects of **Building-Induced Wake Effects** on or near airports.

The Role of Changes in Windflow Conditions on Aircraft Stability

One of the fundamental characteristics of aircraft stability is the "lift" condition which is responsible for keeping an airplane airborne. At some critical oncoming wind angles, the amount of lift can effectively drop to zero – this condition, termed "stall", creates a critical stability condition for any airplane. In addition, during the last stages of landing, flare, de-crab and high speed roll take place. In such situations, any **relatively sudden and sustained change** in oncoming windflow condition can present a potential problem to aircraft stability, flight handling and landing performance.

Weather-Related Turbulence and Windshear

It is clear from well-documented experience that weather events such as downbursts or microbursts can create adverse windflow conditions which put aircraft stability at risk.

Building-Induced Wake Effects

Limited experience exists in relation to adverse aircraft events associated with building-induced wake effects. However it is clear that such wake flow effects are "real" and can reach a magnitude, given the right combination of building-runway proximity and building shape and size, which suggests a need for guidance to be provided for the safe operation of airports.

Available Guidance

Very little guidance currently exists. For example, the recently updated Application for Development Approval used by Sydney Airport (SACL, May 2010), contains a Note 8 section which requires the proponent of a new development to carry out a Review of Environmental Factors whose Scope of Works must consider **wind shear and turbulence**, OLS intrusion, safety and security, lighting impacts, bird-dust-hazard management, fire management and a T1 MUIP. No guidance however is given as to what would constitute an appropriate methodology to carry out such an assessment in relation to wind shear and turbulence, as opposed to well-understood methodologies for carrying out lighting studies, etc. For example, when is a "qualitative" assessment based on best engineering judgement adequate in comparison to a more "quantitative" type assessment involving wind tunnel model scale testing or computer simulation using CFD (Computational Fluid Dynamics).

- The Australian Airports Association (AAA) has said that the assessment of potential windshear effects on airport operations is essential to the viable operation of airport infrastructure. The AAA's position is that for proposed developments on-airport, the assessment should be made as a matter of course for any developments within a defined area around runways.
- Amsterdam's Schiphol Airport uses a **1 in 35** rule (building height to runway distance from building) as an initial acceptance criterion. However, it has been suggested that this could be potentially conservative for buildings of certain shapes and aspect ratios (height to width to depth) which do not produce extensive and hence problematic wake regions of concern.

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Scope of the Present Study

The scope of the present study has been broken up into the following sections:

Part A

- In this section, SLR has carried out reviews of (i) relevant ICAO guidance material and (ii) existing research and approaches used to assess world's leading practice.

Part B

- In this section, the criteria which would trigger a detailed assessment of the potential for building-induced wake effects to affect the safety of operations at airports are established.

Part C

- In this section, guidance is provided regarding the design and positioning of structures in relation to runways to minimise effects on aircraft operations.

Part D

- This section provides guidance on other options to mitigate building-induced wake effects for existing structures where potential safety risks are identified.

Key Outcomes - Part A

Section 2 dealt with the sources of windshear and turbulence that can be encountered by aircraft, especially during the crucial take-off and landing stages.

- It was seen that windshear and turbulence can arise from **natural weather phenomenon** (like microbursts), from the **built environment** and in other "man-made" circumstances (eg the **vortex wake flow** behind jet aircraft)
- In terms of building-induced wake effects, some initial descriptions of wake flow, vortex shedding and the variations in location and time induced by the variations of oncoming windflow provided an early indication that building wakes can take complex form depending upon the shape, dimension and orientation of the building concerned.

Section 3 dealt with the issue of aviation windshear risk and provided case studies primarily related to weather-induced windshear.

- This class of windshear event led to the development of sophisticated wind monitoring systems deployed around airports which in turn led to an understanding of the magnitude of windshear likely to cause flight difficulties, especially during take-off and landing.

Section 4 provided case studies involving building-induced windshear (and turbulence), including Australian case studies (at Canberra Airport).

- The circumstances under which building-induced windshear (and turbulence) arise suggest that building-induced windshear events of concern would arise less frequently than weather-induced events (eg from microbursts, gust fronts, etc).
- However, it is likely that the frequency of building-induced windshear events will rise in coming years, in response to (a) the ever-growing pressure on airport operators around the world to maximise the value of the seemingly large areas of available land on their premises and (b) increased air traffic and the move towards larger aircraft utilisation (which have the perception of being able to cope with more difficult windflow circumstances) leading to an increase in the likelihood of aircraft using runways under strong crosswind conditions.

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Section 5 provided a summary of world-wide response to building-induced windshear in terms of regulation and guidance material. This has taken primarily two forms.

- "Management" Tools: in Australia, this may be in the form of aerodrome information contained in an ERSA guidance note (eg Canberra Airport has one for Runway 35). In the UK, this may be in the form of an AIP guidance note (eg London's Heathrow Airport has one for Runway 27R and Runway 27L).
- Positional "Rules": An example is the 1:35 rule which arose from the detailed studies of building-induced windshear undertaken at Amsterdam's Schiphol Airport

Key Outcomes - Part B

Section 6 included a detailed exposition of quantitative studies (involving wind tunnel testing and/or CFD) describing the extent of the wake disturbance behind primarily regular building shapes (ie rectangular, sharp-edged buildings).

- The wake disturbance behind bluff bodies (ie buildings) impacts both the mean speeds and turbulence of the oncoming windflow.
- The most readily identifiable feature of the wake is the low-speed "cavity" region of re-circulating flow immediately behind the building. This typically extends up to around 5 times the building height.
- Wake effects however (both in terms of mean wind speed deficit and increased turbulence) extend well past the recirculation zone, in some cases (depending upon building orientation) to beyond 20 times the building height.
- The extent of the wake (ie the region of disturbance to the upstream flow) – in terms of its physical dimension and the magnitude of the disturbance contained therein – will depend upon building shape (eg square, rectangular, etc), building orientation (ie building facades perpendicular to the wind, facades at 45º to the wind, etc), aspect ratio (height to building width ratio) and surrounding terrain conditions (open country terrain, suburban terrain, etc.
- A particular case of interest is when certain building shapes are oriented at an oblique angle to the approaching windflow. In this case, a pronounced "delta" vortex forms at the leading corner of the building which persists for many building dimensions downstream. Tests indicate that increased turbulence levels exist well beyond the point where the mean wind is restored to its upstream (unaffected) level.
- **Section 6** showed that a **simple "*one-size-fits-all*" rule** for determining the magnitude of wake disturbance (for both mean winds and turbulence levels) **based just on building height**, and accurate for any building shape and any combination of building dimensions and building orientation, **is not apparent**. For example, two rectangular buildings with exactly the same ratios of width-depth-height but of different actual scale (eg one twice as big as the other) result in different wake impacts relative to their heights.
- If it was desired to determine the extent of building wake effects using a simple *"one-size-fits-all"* prediction rule based for example on the number of building heights downstream, such a rule would have the potential to end up being **highly conservative** if it was required to cover a reasonable range of building shapes, dimensions and orientation.
- **Section 6** established some useful benchmark values for building-induced wake effects for rectangular buildings in upstream open terrain conditions and for the case of no flow re-attachment (ie building width perpendicular to the flow greater than building length in line with the flow).

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- A reasonable estimate for the **potential maximum magnitude of horizontal windshear** (of the mean wind) experienced by an object moving across a building wake (close to the ground) is simply the **magnitude of the mean wind speed at top of building height in the approach flow**. Important considerations follow on from this observation.
- The potential maximum magnitude of horizontal windshear (of the mean wind) experienced by an object moving across a building wake will **increase with building height**.
- The potential magnitude of horizontal windshear (of the mean wind) experienced by an object moving across a building wake will be highest if the terrain conditions upstream of the building are "smooth", ie "open" flat terrain.
- **Table 5** of **Section 6.8** provides a set of estimates which can be used to determine the magnitude of mean crosswind deficit of an object moving across the wake behind a building, for the case of a rectangular building, height between 30 m to 40 m, no re-attachment, open country terrain.
- The **Table 5** estimates are given as a ratio of upstream mean wind speed, V_H (at building height, H). This then provides a direct link with which to establish the likelihood or frequency of occurrence of wake-induced horizontal windshear events of a given magnitude. This frequency of occurrence can be readily determined by calculating the frequency of occurrence of the mean wind speed at the height of the top of the building of concern, taking into account the surrounding terrain and the optimal directionality which has the potential to produce wakes interacting with airport operations.

Section 7 included a detailed examination of the three primary tools available for determining the extent of the wake disturbance behind buildings:

- Qualitative - "Desktop", "Expert Opinion"
- Wind Tunnel Testing (Quantitative) - Using Scaled Models of the Building and Wind
  - ✓ SAND SCOUR, SAND EROSION, OIL STREAKLINE
  - ✓ DISCRETE SENSOR - using either IRWIN or HOT-WIRE SENSORS
  - ✓ PARTICLE IMAGING VELOCIMETRY (PIV)
- CFD Modelling (Quantitative) - 3-D Computer Simulation

Some explanation was provided as to the reasons why **qualitative studies** (based on the best engineering judgement of wind engineers) can lead to **variable** and **sometimes unconservative estimates** of the potential extent of downstream building wake influence.

It is equally clear that the **wind tunnel and CFD options** provide **reliable and quantitative outputs** in terms of the extent of building wake disturbance (for both mean winds and turbulence levels).

Section 8 provided three examples of quantitative studies of building wake assessment using the wind tunnel and CFD illustrating the usefulness of such techniques in establishing reliable estimates of the extent of the wake disturbance behind buildings (of any shape).

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Key Outcomes - Part C

Section 9 described the aviation regulatory framework in Australia and the degree to which on-airport building developments are controlled via OLS rules.

Section 10 provided a risk-based approach to the control of on-airport building developments dependent primarily upon building shape, dimension and orientation.

- It was firstly noted that a simple "one-size-fits-all" building height multiplier rule for assessing the acceptability or otherwise of building projects would have obvious cost and timing advantages, by obviating the need for detailed wind assessments.
- Examples of such rules are the Schiphol 1:35 rule or SACL's suggested 1:10 rule - where the ratio is taken to be the height of the building of interest compared to the distance from the runway centreline.
- On the basis of the building wake characteristics examined in this study and aviation incident reports, it is likely that such a rule would have to be highly conservative to capture a reasonable range of potential building shapes and configurations.
- While easy to apply, such a conservative rule would probably exclude a large number of developments which, under proper detailed assessment, might have easily passed the acceptance criteria adopted for the project.
- **Section 10** therefore provides a three-step process involving both qualitative and quantitative methodologies depending upon building shape, dimension and orientation, with the qualitative option guided by the **Section 6** data for simple rectangular building shapes and the quantitative options leading to a choice of either wind tunnel testing or CFD modelling.

Key Outcomes - Part D

Section 11 provided options for mitigating building generated turbulence and windshear for existing structures where safety risks are identified.

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1 INTRODUCTION AND STRUCTURE OF REPORT

SLR Consulting Australia Pty Ltd (SLR) has been commissioned by the Department of Infrastructure and Transport (the Department) to develop suitable **Guidance Material** covering the effects of **Building-Induced Wake Effects** on or near airports.

1.1 Scope of the Study

The study has been broken up into the following sections:

1.2 Nomenclature

NTSB	(US) National Transportation Safety Board
ICAO	International Civil Aviation Organisation
FAA	(US) Federal Aviation Administration
BoM	(Commonwealth) Bureau of Meteorology
AGL	above ground level (ie as in height AGL)
TDWR	Terminal Doppler Weather Radar
LLWAS	Low Level Windshear Alert System
Knot	Nautical Mile per Hour (abbreviation, kt) Conversion factors: 1 kt = 1.852 km/hr = 0.514 m/s
2-D, 3-D	2-dimensional, 3-dimensional

PART A

A Review of Relevant ICAO Guidance Material and Existing Research and Approaches Representing World's Leading Practice

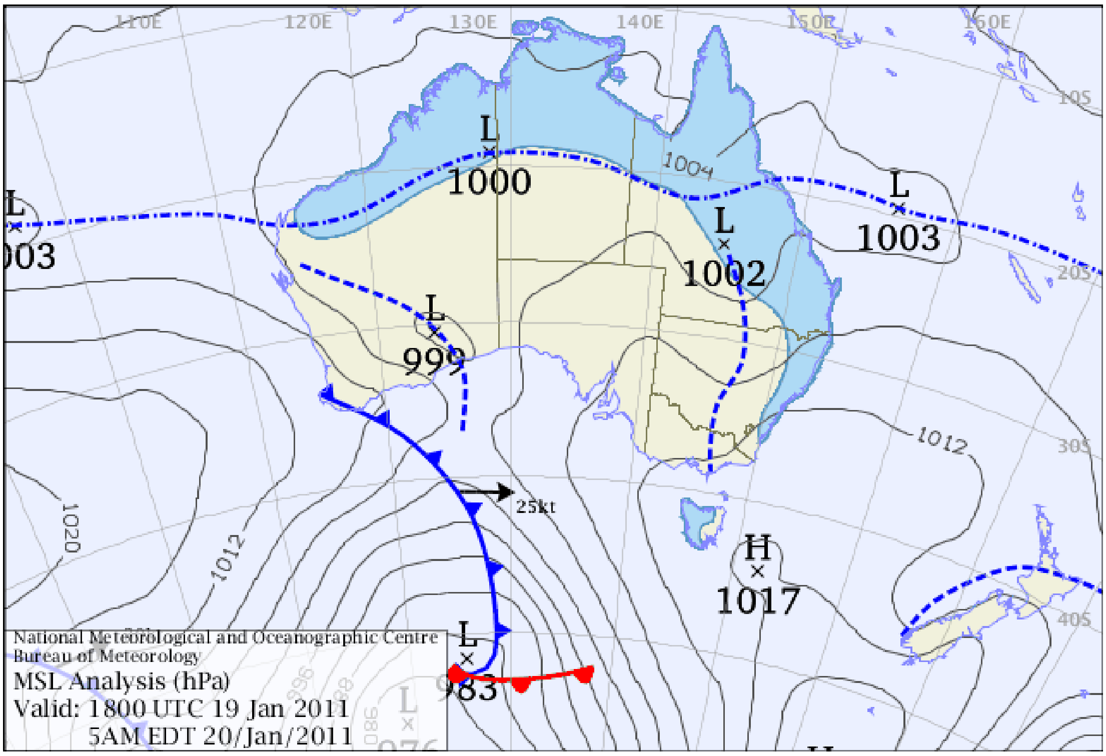
2 ATMOSPHERIC WINDFLOW AND WINDSHEAR

2.1 How Does Wind Arise ?

Solar radiation reaching the earth varies both latitude-wise (strongest at the equator and weakest at the poles) as well as time-wise. The subsequent absorption and reflection of this radiation also varies spatially according to local surface characteristics (eg for different surface albedo conditions).

These variations result in temperature differentials and hence pressure differentials which are further influenced by the rotation of the earth about its own axis. The result is atmospheric pressure systems (eg lows and highs) as seen on weather maps such as the example shown in **Figure 1.**

Figure 1 Example Weather Map – Pressure Systems over Australia, 20 January 2011



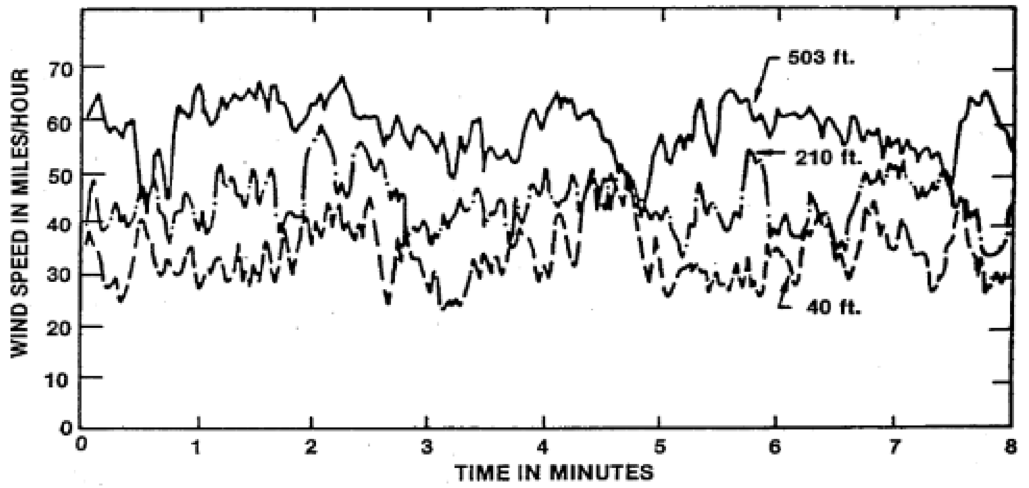
The pressure gradients which accompany weather systems like the ones shown in **Figure 1** cause the acceleration of air, resulting in atmospheric windflow. The resulting winds at any one location are a balance between the forces of pressure gradient, the air's centripetal acceleration (eg in the Southern Hemisphere the air circulates clockwise around low pressure systems) and the Coriolis Force (caused by the earth's rotation).

Well above the earth's surface, the resulting force-balanced wind is termed the **Gradient Wind Speed, V_G**. The gradient wind speed is the wind commonly heard over the news in weather forecasts and often expressed in units of **km/hr** or **knots** (1 kt = 1.852 km/hr = 0.514 m/s). The term "knots" is commonly (and internationally) used in aviation circles.

2.2 Windflow over the Earth's Atmospheric Boundary Layer

As noted in **Section 2.1**, the passage of weather (pressure) systems over the surface of the earth generates accompanying airflow. At any one particular location, wind speed measurements taken at different heights above the ground during the passage of such weather systems would look like the historical wind traces shown in **Figure 2**.

Figure 2 Sample Wind Traces Recorded at Different Heights above Ground Level



Record of wind speed at three heights on a 500 ft. mast

The following can be seen in **Figure 2**.

- Clearly, even at one particular location and one height, the wind is not "steady" (ie constant in magnitude). Instead, the wind appears to fluctuate above and below an average level:
  - The average magnitude of the wind is termed the "**mean**" wind
  - The fluctuating component of the wind (above and below the mean) is called the "**turbulence**"
- In relation to the **mean** wind speed:
  - The mean wind speed decreases closer to the ground. This reduction occurs because of the frictional drag imposed on the wind by obstacles on the earth's surface (trees, buildings, etc).
  - The mean wind speed does not keep increasing with height forever. Eventually it reaches an asymptote hundreds of metres above the ground where it no longer experiences any friction from below – this asymptote is the **gradient wind speed** discussed in **Section 2.1**.
  - In essence, weather systems determine the magnitude of the gradient wind speed aloft and friction from the earth's surface influences the wind (slowing it down) close to the ground.
- In relation to the **fluctuating** component of wind speed or **turbulence**:
  - The magnitude of the turbulence appears to be relatively similar at all three heights.
  - The turbulence appears to be made up of a range of fluctuating components, varying from seconds (local peak gusts) to many minutes.

The **turbulence intensity** is equal to the ratio of the turbulence over the mean.

Wind direction also varies (just like the wind magnitude) due to the three-dimensional (3-D) nature of turbulence (discussed in the next section).

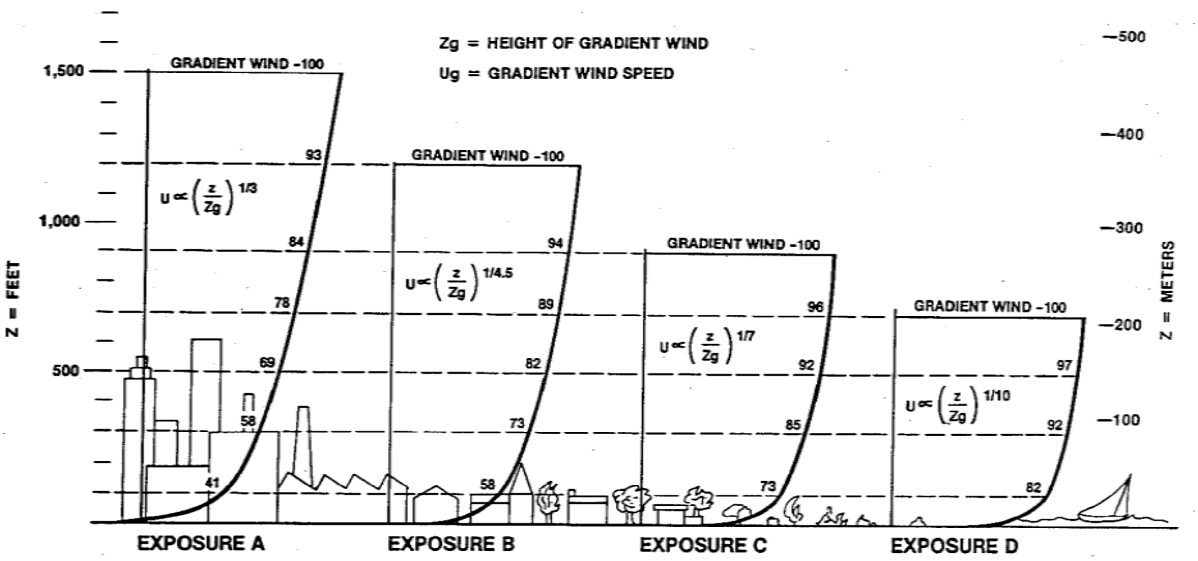
2.3 Atmospheric Boundary Later Characteristics and Windshear

The zone where the mean wind varies with height due to friction imposed by the earth's surface is called the earth's **planetary** or **atmospheric boundary layer**.

The characteristics of this boundary layer (eg its depth and how quickly mean winds reach their asymptotic gradient value above) vary over surfaces with different "roughness" characteristics, eg flat, open terrain versus highly built-up urban terrain. This can be seen in **Figure 3** (taken from ANSI A58.1-1982) where the following features can be seen:

- The depth of the boundary layer varies with surface roughness.
  - Over open, flat terrain (minimal roughness) the boundary layer depth is modest (<200 m).
  - In the middle of dense urban environments (large cities with tall skyscrapers), the depth of the boundary layer can reach up to 500 m or more.
- Close to the ground (eg at 10 m AGL), the ratio of mean wind speed to the gradient wind speed also varies significantly with surface roughness.
  - Over open, flat terrain (minimal roughness), mean wind speeds at 10 m AGL are as high as 60% or more of their gradient value aloft.
  - In the middle of dense urban environments (large cities with tall skyscrapers), mean wind speeds at 10 m AGL can be 40% or less than their gradient value aloft.

Figure 3 Mean Wind Profiles Over Different Surface Roughness Categories (Flat Ground)



In subsequent sections of this report, the term windshear will be described both in a general sense and specifically in relation to aviation safety. In a general sense, **windshear** can be thought of as any change of wind speed magnitude and/or wind direction. Furthermore, windshear can imply a change in either the mean wind or the turbulence.

The profiles of mean wind shown in **Figure 3** show that there is a change in mean wind speed with height for different surface roughness conditions. In this report, this form of windshear is termed **Boundary Layer Windshear, BL-Wsh**.

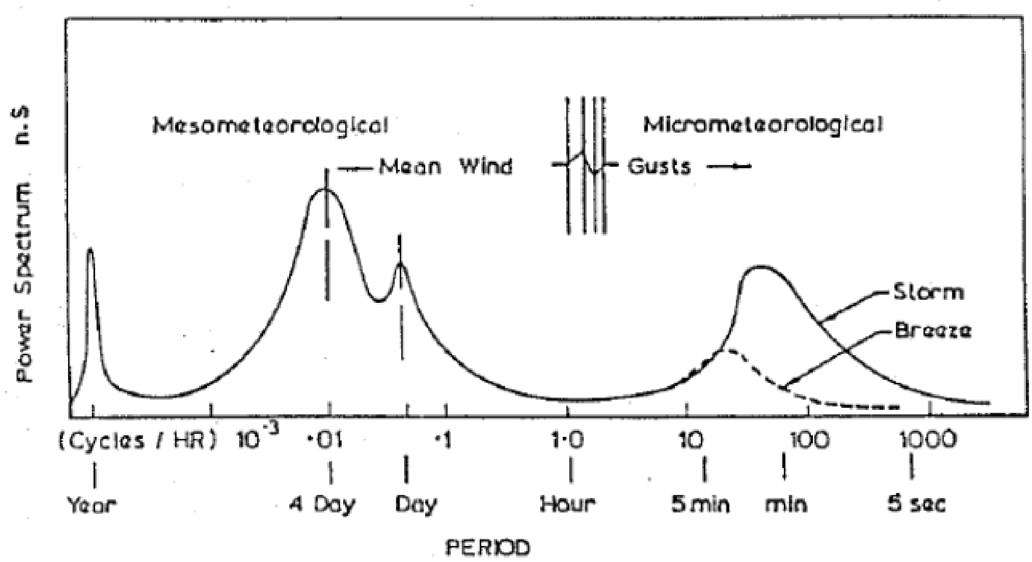
2.4 The Nature of Turbulence

Turbulence denotes the fluctuations which occur above and below the mean wind, both in terms of wind speed magnitude and direction. The mean wind itself varies as well (although much more slowly) and hence it is important to distinguish between such variations. Fortunately, such variations can be separated out into two distinct frequency regions of interest by examining the **power spectrum** of wind.

Figure 4 shows an idealised wind power spectrum which would be obtained by recording wind speed over a very long period of time at a wind monitoring location. The power spectrum is quite simply a graphical representation of the distribution of energy contained in the wind differentiated by frequency. The “spectral gap” evident in the graph (at a period of ~1Hr) provides a convenient way to separate out the “mean” wind and “turbulence” into two broad regions.

- The micro-meteorological region contains fluctuations occurring over the course of seconds and minutes. We generally call such fluctuations “gusts”. This region is reserved for the term “turbulence” and has a peak at around 1 cycle/minute.
  - The overall size of the spectrum in this region reflects the extent of turbulence: storms exhibit greater fluctuations or greater turbulence than mild breezes.
- The meso-meteorological region has three sub-peaks at one per day (reflecting day-night variations), 1 per 4 days (reflecting the time it typically takes weather systems to pass over a particular location on the earth’s surface) and 1 per year (characterising annual seasonal weather patterns and their influence on wind speed and wind direction).

Figure 4 Idealised Long-Term Power Spectrum of the Wind



It is of interest to note that, within the higher frequency range of the gust spectrum, the shape of the curve is governed essentially only by the gust wavelength (size of the gust) and a quantity known as the rate of viscous dissipation of energy per unit mass (**EDR** or **ε**). This dissipation rate parameter balances the rate of production of turbulence and is hence a fundamental characteristic of the overall degree of turbulence present in any windflow. This explains why **EDR** has been chosen as the measurement parameter of choice for leading-edge windshear and turbulence warning systems deployed around some of the world’s major airports.

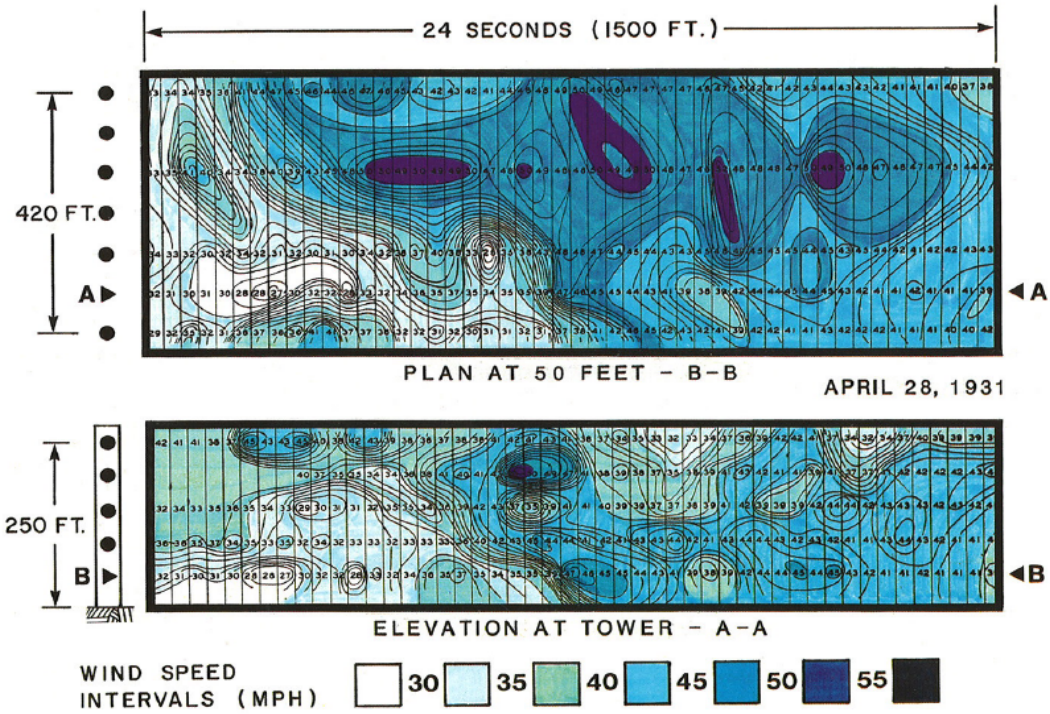
While the technical description of turbulence is often framed in terms of frequency and wavelength or even more complex technical parameters such as the viscous energy dissipation rate, **EDR**, it is instructive to be able to visualise what turbulence actually looks like in the real world.

Figure 5 shows sample cross-sections of wind recorded near Ann Arbor (Michigan, USA) during the passage of a series of winter storms in 1931, the first (known) such depictions of 3-D turbulence. The top figure is a horizontal slice of wind obtained from anemometers located on a line of 50-foot high recording masts. The lower figure is a vertical slice of wind obtained from a series of anemometers mounted vertically on a single 250-foot high recording mast.

The 3-D physical nature of the turbulence within the wind is clearly evident as well as its relationship to the frequency wind spectrum.

- At one end of the turbulence spectrum are low frequency gusts – these are larger in size (tens of metres in typical dimension) where the air slowly revolves around, as the gust is carried along by the mean windflow. This is in fact where turbulence is created, ie windflow over the surface of the earth produces large 3-D gusts which move in the direction of the mean windflow.
- At the other end of the turbulence spectrum are high frequency gusts – these are much smaller in size (metres or less) where the airflow is highly rotational and where short-term peaks in wind magnitude occur. This is the “cascade” region where energy is dissipated - physically speaking, it is where larger gusts break down into ever smaller gusts.

Figure 5 “Snapshots” of Turbulence



It should now be clear why the wind traces recorded at a single anemometer at a given location appear like the sample traces shown in **Figure 2**, with occasional sharp peaks coinciding with the passage of more intense gusts which are interspersed in between lulls coinciding with larger (long wavelength) gusts.

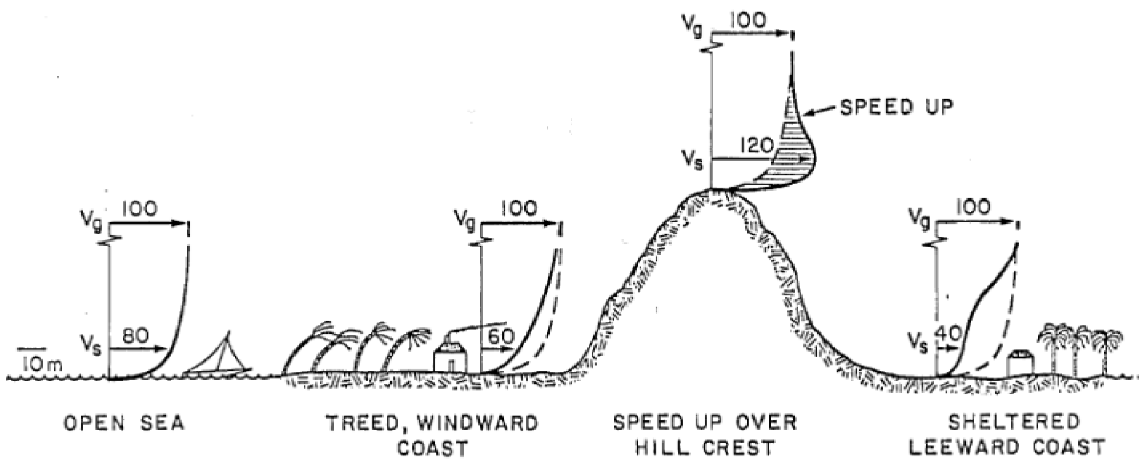
The fact that the air within these 3-D gusts is circulating also explains why turbulence (ie the fluctuation of wind) causes changes in both wind direction as well as wind speed (magnitude).

2.5 The Influence of Topography

The term **"terrain"** is used in normal wind engineering parlance to describe variations in the roughness of the earth's surface (eg open terrain, urban terrain, etc); **"topography"** is used to describe undulations or changes in elevation, eg hills, ridges, valleys, escarpments, etc. Variations in topography can have as great if not greater impact on windflow than variations in terrain. **Figure 6** shows a weather system approaching the coast with a gradient wind speed of 100 km/hr.

- The weather system is initially over water (flat, open terrain)
  - The gradient wind speed is 100 km/hr; mean winds near the surface are 80 km/hr and the turbulence is low.
- The weather system now passes over land near the coast with modest roughness
  - The gradient wind which is still governed by the weather system remains at 100 km/hr. Mean surface winds however reduce to 60 km/hr and the turbulence increases in response to the increase in surface roughness (houses, trees, etc).
- The wind now passes over a significant hill
  - The gradient wind speed remains unchanged. The mean wind now experiences a wind **speed-up** as it accelerates over the hill and is now 120 km/hr. The corresponding change in turbulence is complex and affected by the local roughness, slope of the hill, etc.
- The wind now passes into a shielded area.
  - There is still no change to the gradient wind speed (still governed by the weather system aloft). The mean wind speed close to the ground now falls to 40 km/hr, much lower than its original magnitude. The turbulence is complex, depending upon on the proximity to the hill and flow re-circulation is even possible.

Figure 6 Influence of Topography on Wind Profiles



When the topography illustrated in **Figure 6** takes the form of a ridgeline or escarpment which is not oriented perpendicular to the oncoming direction of the wind, even more complex wind changes can take place, whereby the apparent direction of the wind (and not just the magnitude) can change in response to the topographical variations encountered.

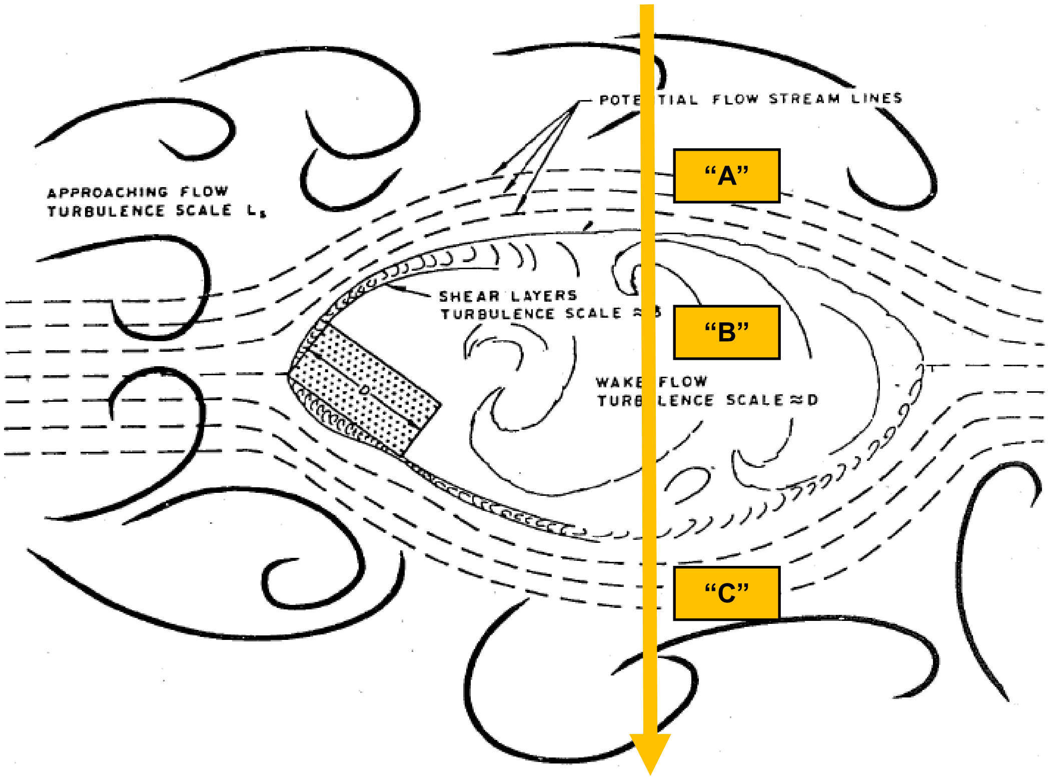
In this report, the potentially significant windshear which can result from changes in local topography is termed **Topography-Induced Windshear**, **TI-Wsh.**

2.6 The Influence of Buildings

A Simple 2-Dimensional View

The windflow around "**bluff**" bodies (eg buildings) produces a characteristic and highly localised disturbance to the prevailing mean wind and turbulence as shown in **Figure 7**, termed the "**wake**".

Figure 7 Turbulent Windflow Around a Bluff Body



Three distinct flow regions can be discerned:

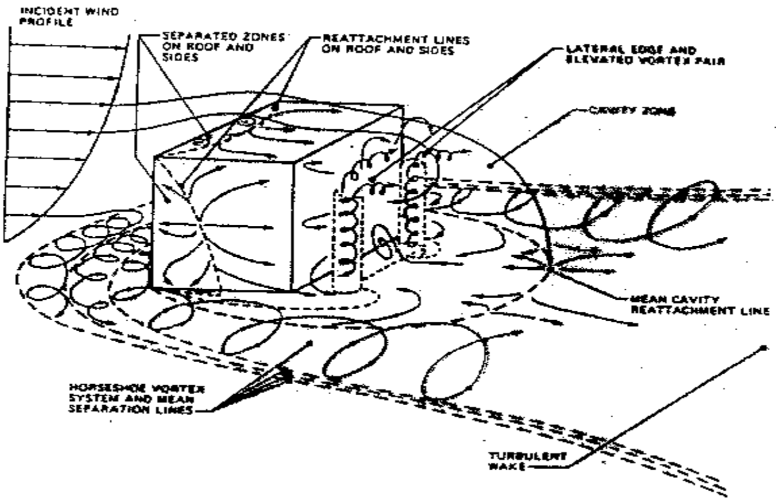
- Starting with the approach flow, the mean windflow gradually curves around the body and re-unites some distance downstream. In this region, the approach flow turbulence level remains reasonable steady.
- Behind the body is a sheltered region within the wake known as the "**cavity**" or "**bubble**" region where the windflow is greatly reduced in magnitude and air flows in all directions. Large horizontal eddies can form in this region allowing some of the flow to move back towards the body, which is why the cavity region is called a "**recirculation**" zone.
- In between these two regions and commencing at the point on the body where the approach flow "**separates**" from the body is a narrow transition area or **shear layer zone**.

An object moving along the orange arrow shown in **Figure 7** would experience: firstly "A" a strong (left-to-right) crosswind, then "B" a lull where the wind might even be moving right-to-left and then "C" a strong (left-to-right) crosswind again. The change in turbulence intensity encountered during this passage would be equally dramatic – with much higher relative wind fluctuations encountered within the cavity region of the wake.

Bluff Body Wake Effects in 3-D – Single, Regular-Shaped Buildings

The simplified 2-D flow shown in **Figure 7** takes a 3-D form in response to the size and shape of the bluff body (building). This can be seen in this classic figure reproduced in many wind engineering texts depicting the “wake” flow created behind a single rectangular-shaped building (refer **Figure 8**).

Figure 8 3-D Wake Flow Behind a Bluff Body

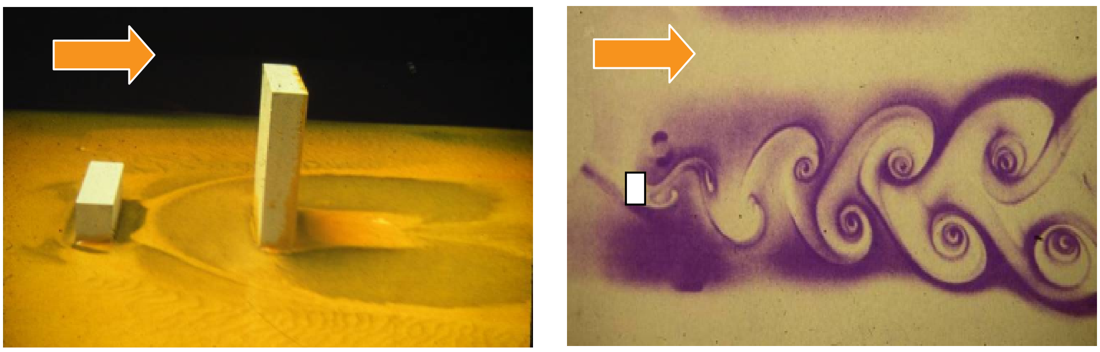


More Complex Wake Effects - Multiple Buildings and Vortex Shedding

The presence of multiple buildings produces variations on such wake flow as seen in **Figure 9a**.

Another other important wake flow feature associated with certain building shapes is **vortex shedding**, whereby a regular stream of “eddies” or “vortices” are generated as windflow moves past a building. These vortices alternate either side of the building and move downstream with the main flow – refer **Figure 9b**. Their formation is influenced by building shape and they can persist for many building dimensions downstream of the building.

Figure 9 (a) Multiple Building Wake Effects, (b) Vortex Shedding Wake Effects



Unsteady Wake Behaviour

It is rare for the any of the above windflow patterns to remain “steady”, either time-wise or location-wise. This is because the oncoming windflow which creates the wake features shown above is itself unsteady, especially in terms of wind direction. Thus building wakes themselves exhibit variations (time-wise and location-wise) in response to changes in upstream wind conditions.

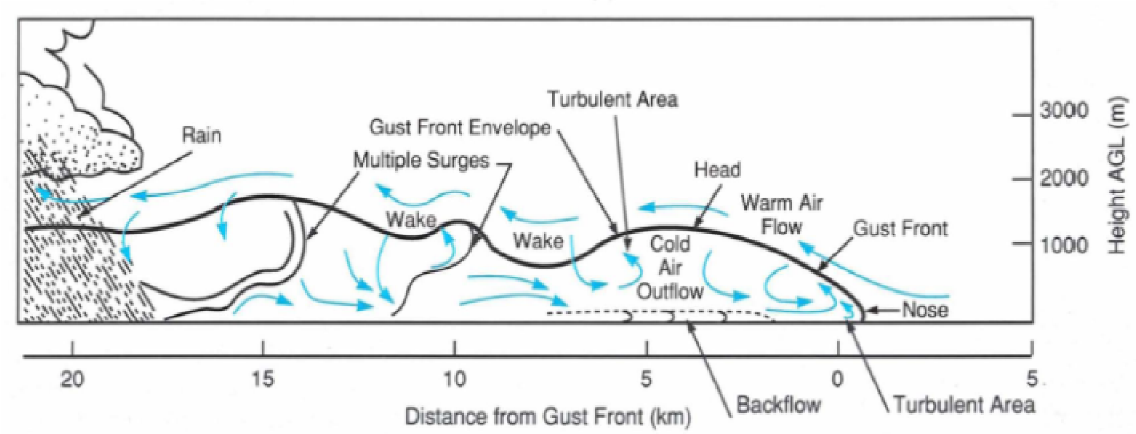
In this report, the above windshear is termed **Building-Induced Windshear**, **BI-Wsh.**

2.7 Complex Weather Systems and Associated Windshear – Gust Fronts

Up to now, the wind conditions described in previous sections apply to more-or-less "steady-state" atmospheric wind conditions where the windflow is primarily horizontal. In many cases, unstable pressure systems or adjacent (interacting) pressure systems result in complex convective behaviour (ie unusual windflow behaviour in both a vertical as well as horizontal sense), especially in the case where two interacting systems have significant differences in their air temperatures.

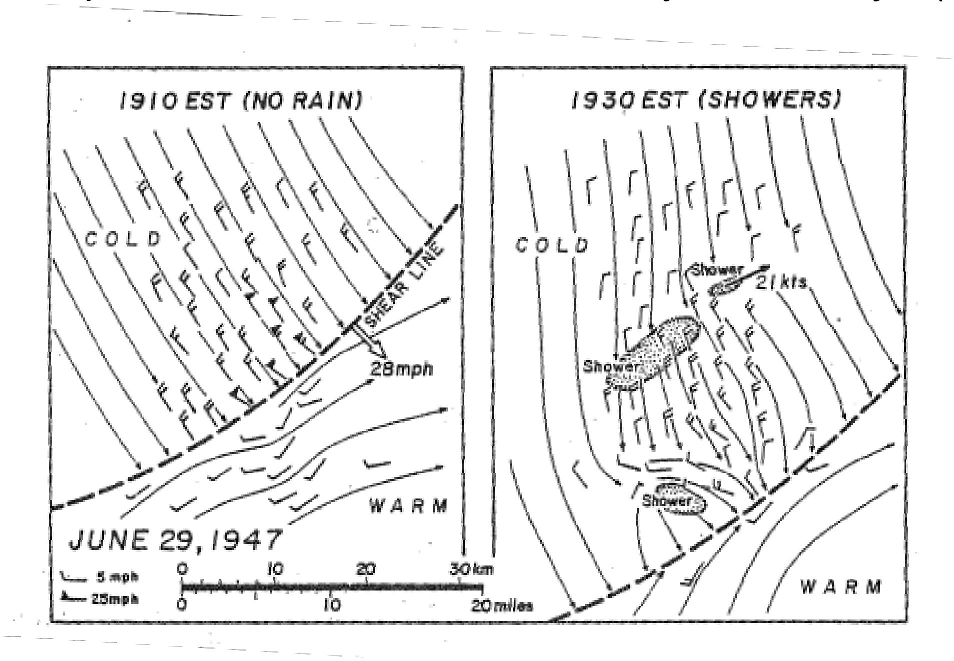
A common example of such behaviour is the "**gust front**". Gust fronts result from thunderstorm outflows whose leading edges propagate away (generally in a more or less constant direction) from the main precipitation area, as shown in **Figure 10**.

Figure 10 Idealised Description of a Thunderstorm Gust Front



One of the earliest documented investigations of gust fronts was by Byers (1949) who was able to capture surface winds during thunderstorm events in Florida (1947) and Ohio (1948) via a wide ranging network of monitoring stations. **Figure 11** shows an example of a gust front moving towards the southeast (at 28 mph). Ahead of the gust front is a warmer area with mild southwest winds of around 5 knots. Behind the gust front is a colder outflow area with much higher (over 50 knots) northwest winds. Another interesting aspect of these windflow patterns is the non-uniformity of wind direction which occurred once heavy rain commenced within the outflow area.

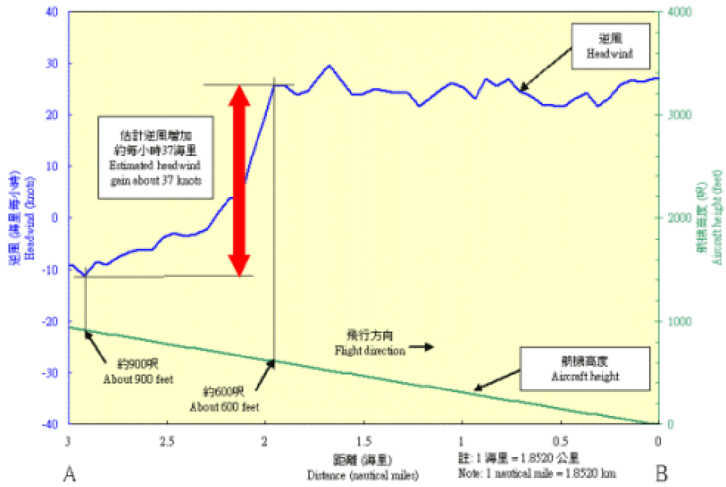
Figure 11 Example Wind Patterns from the Thunderstorm Project Network – Byers (1949)



Clearly, an airplane with a flight path intersecting a gust front would experience a significant change in winds encountered, both in terms of mean wind (speed and direction) and turbulence. Indeed, this advice is provided in numerous references, including the Aviation Weather Services Advisory information issued by the Hong Kong Observatory – refer **Figure 12**. The diagram shows the headwind (vertical axis) recorded during a landing which occurred in the midst of a gust front event where the airplane experienced a **37 knot change in headwind** over approximately 1 km distance just over 2 km out from landing at Chep Lap Kok Airport.

In this report, the above windshear is termed **Gust Front Windshear, GF-Wsh.**

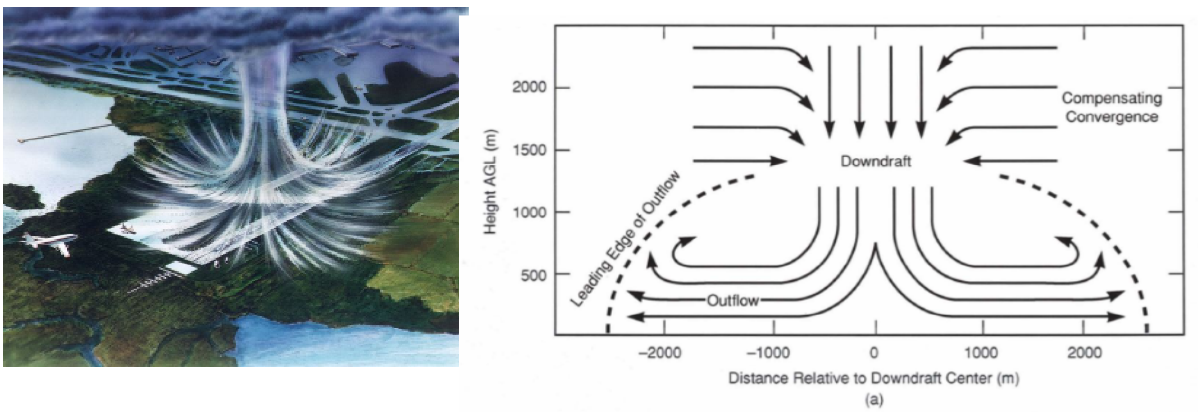
Figure 12 Hong Kong Observatory Advisory Information re Gust Front Incident



2.8 Complex Weather Systems and Associated Windshear – Microbursts

T. Theodore Fujita was instrumental in identifying a particular type of weather system of specific importance to aviation safety, namely the downburst phenomenon known as a "**microburst**" – refer the illustrative depictions in **Figure 13**.

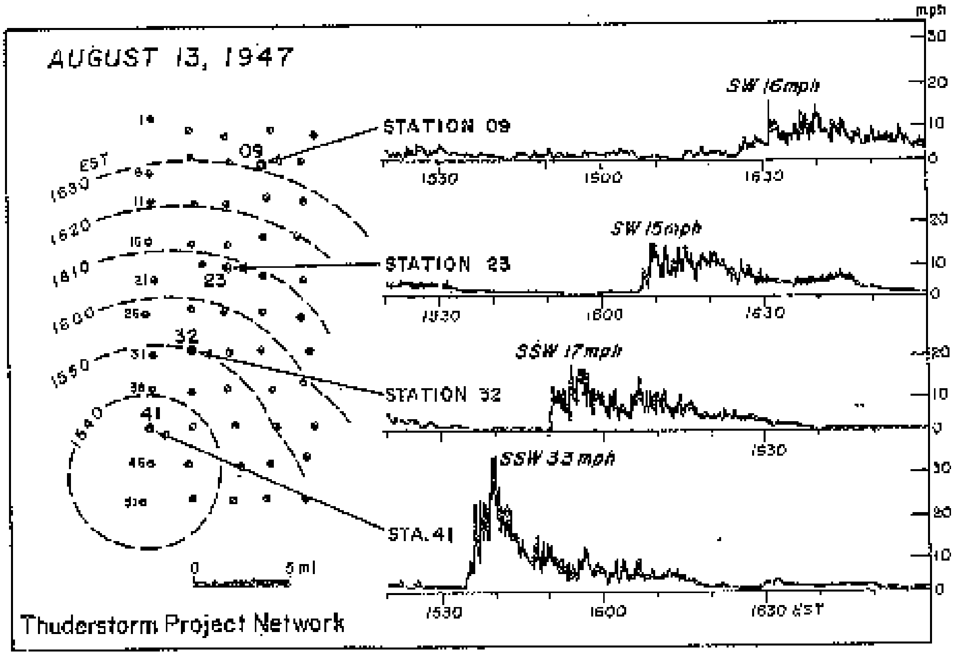
Figure 13 Illustrative Depiction of a Microburst



A microburst is a transient event which starts out as a downward flow which then spreads out horizontally in all directions. **Figure 14** shows a series of wind records obtained from monitoring locations positioned radially outwards from a downburst event. It can be seen that the peak speeds recorded at each station gradually decreased as the leading edge of the downburst spread outwards.

In this report, the above windshear is termed **Microburst Windshear, Mb-Wsh.**

Figure 14 Progression of Winds Recorded During a Downburst Event



2.9 Other Types of Windshear

There are other types of windshear of interest to aviation safety. One final category worthy of mention is that of **Wake Vortex Windshear, WV-Wsh**, which relates to the vortices formed by the pressure differential of lift forces over the wing surfaces of an aircraft. These vortices are yet another manifestation of the vortex phenomenon described in Section **2.6**. They are of particular importance at airports which have closely spaced parallel runways in terms of the safe time and distance separation which planes need to maintain when landing or taking off from parallel runways.

Figure 15 Wake Vortices Behind Airplane Wings

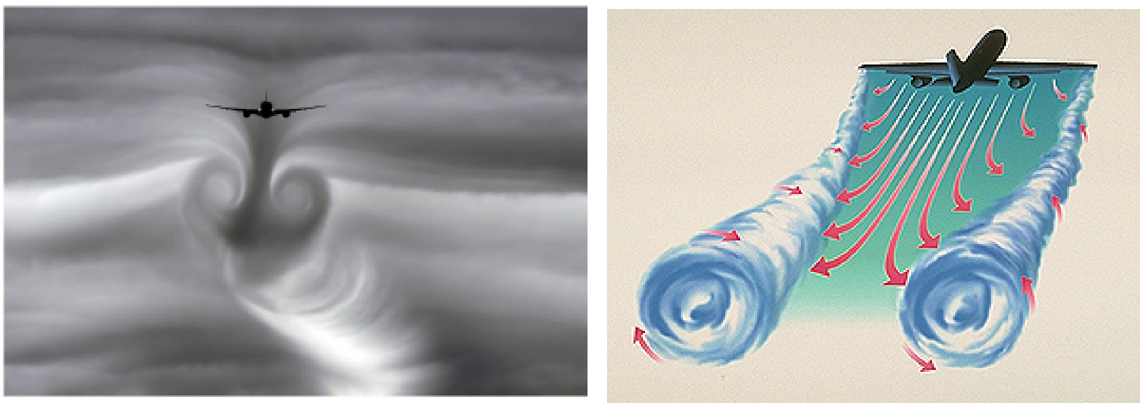


FIGURE 2-2 The vortex wake behind lifting wings descending through a thin cloud layer. SOURCE: Airliners.net. Photo courtesy of S.C. Morris.

2.10 Summary of Primary Windshear Types of Interest

In general, windshear can be thought of as any change of wind speed and/or wind direction. In so far as aviation safety is concerned, windshear events of particular concern usually have two additional characteristics, namely that …

(a) the change in wind speed/direction occurs close to the ground when an airplane's speed is low and the pilot's response options (especially during take-off and landing) are limited, and

(b) the change in wind speed/direction is sustained over a time/length scale of significance relative to typical aircraft speeds.

This is why microbursts are of such concern in relation to aviation windshear safety – they produce large changes in wind speed and wind direction close to the ground in both a vertical and horizontal sense and their physical scale is significant in terms of airplane paths during take-off and landing.

It is useful to distinguish between the various primary types of windshear because their characteristics suggest the means by which they can be identified, quantified, categorised into different risk classes and hence managed, especially in relation to wind monitoring systems deployed at airports and the kind of warning reports that would be useful to pilots.

Table 1 summarises the main forms of windshear discussed in this report.

Table 1 Primary Categories of Windshear

Windshear Type	Key Distinguishing Characteristic
Boundary Layer **BL-Wsh**	Archetype variation in wind speed within the earth's atmospheric boundary layer caused by the friction of surface obstacles such as trees, buildings, etc, and the resulting slowing down of airflow close to the ground. Mean winds increase with height above ground; turbulence levels vary with wind strength (turbulence activity within a storm is greater than within a breeze).
Gust Front **GF-Wsh**	Region of interacting airflows at the leading edge of a moving thunderstorm system with warmer airflow flowing over the cold air emanating from the thunderstorm with complex vertical airflows in between.
Microburst **Mb-Wsh**	A transient weather event whereby a large mass of air is directed downwards in a concentrated fashion and is then deflected outwards in all directions once impacting on the ground.
Topography-Induced **TI-Wsh**	Changes in mean wind, turbulence and wind direction resulting from windflow over topographic features such as hills, ridges, escarpments, valleys, etc.
Building-Induced **BI-Wsh**	Interruption to the airflow past almost any building shape or "bluff" body involving the creation of a region of quiescent, re-circulating flow (the building wake) with a very narrow transition shear layer separating the surrounding flow from the wake region.
Wake Vortex **WV-Wsh**	Vortices formed by the pressure differential of lift forces over the wing surfaces of an aircraft and the resulting downstream wake trail.

2.11 Section 2 Synopsis

Windflow over the earth's surface arises within the weather (pressure) systems created by a combination of differential heating of the earth by the sun's radiation and the earth's rotation about its own axis.

Even under "normal" (ie non-storm) conditions, the wind is never "constant" – instead it is made up of an average or **mean** component and a **fluctuating (turbulence)** component.

The mean wind and turbulence can be differentiated via the wind power spectrum.

The turbulence within the wind is 3-dimensional in nature, comprising a range of easily identifiable **gusts** which move in the general direction of the windflow and whose size varies from around a metre or so to many tens of metres in diameter.

When horizontal airflow moves over the surface of the earth, frictional forces caused by obstructions such as tress, buildings, etc, slow the wind down. In this region known as the **atmospheric (or planetary) boundary layer**, the profiles of mean wind and turbulence vary according to the terrain types below, eg open country terrain, suburban terrain, heavily built-up urban terrain, etc.

The resulting windshear is termed **Atmospheric Boundary Layer Windshear** **BL-Wsh**

Severe weather systems can produce complex convective behaviour resulting in large vertical and horizontal variations in windflow. Two examples of this are gust fronts and microbursts.

The windshear associated with a gust front is termed **Gust Front Windshear** **GF-Wsh**
The windshear associated with a microburst is termed **Microburst Windshear** **Mb-Wsh**

Topography (hills, ridges, escarpments, valleys, etc) can have a significant impact on any windflow encountering the topography (both in wind speed and wind direction).

The resulting windshear is termed **Topography-Induced Windshear** **TI-Wsh**

Windflow past bluff bodies (ie buildings) also results in significant changes to the resulting downstream pattern of mean wind and turbulence.

The resulting windshear is termed **Building-Induced Windshear** **BI-Wsh**

Finally, other forms of windshear of relevance to aviation safety exist, including the wake flow generated by the parallel vortices arising from aircraft wing lift forces.

The resulting windshear is termed **Wake Vortex Windshear** **WV-Wsh**

All of the above instances of windshear have the potential to impact aviation safety if the associated changes in apparent wind speed and wind direction are encountered in an unexpected manner by an airplane (especially during take-off or landing).

A final comment regarding Section 2 …

This report is dedicated to a study of **BI-Wsh** (**Building-Induced Windshear**) and its impact on Aviation Safety. In this instance, the term "windshear" implies a change to both the mean wind and turbulence in the wake region of a building.

Part of the rationale for including a discussion of the different types of windshear in this section and in the specific choice of references and illustrative figures has been to demonstrate the progress which has been made in terms of our understanding of windshear and the tools available for researchers engaged in such studies over the past several decades.

In **Section 2.4**, it was seen that a proper understanding of turbulence and its physical nature was not possible until wind monitoring instruments were developed which could sample the wind at a high enough rate (sampling frequency) to capture the variations of the fluctuating component of the wind.

Similarly, it was not until the 1970's that our understanding of weather systems coupled with more complex monitoring systems, including Doppler radar systems, led to a better understanding of specific types of windshear events (eg microbursts versus other convective storm activity) and hence the ability to develop warning systems suited to the phenomenon.

Something similar has occurred regarding the issue of building-induced windshear, **BI-Wsh**.

- Much of the early work documenting building-induced wake flows was carried out within the Wind Engineering community, whose primary concern generally was wind loading on structures, as opposed to the evolution of the wake behind a structure. Even studies devoted to the impact of buildings on surrounding pedestrian winds were typically focussed only in the immediate vicinity of a building (where such effects were at their maximum). Thus, studies of building wakes did not generally extend behind buildings to a distance of potential interest to aviation safety (ie many building dimensions downstream).
- In-depth investigations of wakes behind structures have mostly been concerned with structures which exhibit a particular sensitivity to the phenomenon of vortex shedding, typically slender tapered towers of round or square cross-section, eg Sydney's Centrepoint Tower. The wakes behind these structures are usually limited in width and rarely found near airports.
- Within the aviation community, there appears to have been a growing awareness of the phenomenon of building-induced wake effects, but relatively few well-documented investigations. Aviation incident reports (as will be seen in subsequent sections) often contain anecdotal comments (especially from pilots) of higher than normal turbulent conditions under crosswind conditions which suggest interaction of ambient windflow and buildings in close proximity to runway landing and take-off routes.

One of the goals of the present report is therefore to not just to define the circumstances in which wake flows behind buildings can pose a potential threat to aviation safety, but to also ascertain the likelihood of its occurrence, ie its risk profile, of ultimate importance in terms of the extent (and hence cost) of developing systems to minimise its impact on aviation safety.

3 AVIATION SAFETY AND WINDSHEAR

There have now been numerous studies world-wide documenting aviation accidents/incidents where windshear of one type or another was deemed to have played a dominant role.

It is instructive to examine a selection of these to gauge the frequency and magnitude of windshear conditions which have been established as being of concern to aviation safety so that the sub-set issue of building-induced windshear (and turbulence) can be put into context.

These are described in detail in **Attachment B**.

Key summary points only are included below.

Section B1 Key Studies of Relevance to Windshear

This section looks at the important foundation work of Ted Fujita (and his colleagues at IIT) in relation to microbursts and other convective storm activity and the role played by such weather systems in aviation accidents.

Statistics compiled by the National Transport Safety Board (NTSB) in investigating civil aviation accidents in the United States (more than 12,000 incidents investigated since 1967) provide a breakdown showing the proportion of incidents involving weather phenomena such as turbulence and windshear. Data is also provided regarding microburst-related windshear accidents in the period 1975 to 1994 involving 438 fatalities.

Attachment B includes data from incident reports documented in UK Air Accident Branch (AAIB) Bulletins from May 1987 to December 1992 and the percentage involving weather factors, especially wind-related accidents.

Section B2 ICAO (International Civil Aviation Organisation)

The ICAO's Manual on Low-level Wind Shear and Turbulence (Ref 9817) is an invaluable guide to the subject of windshear. The Manual notes that the total number of commercial windshear / downdraught accident deaths since 1943 is 1438 (noting that this is not just large transport aircraft).

Chapter 3 of the Manual provides a comprehensive description of the various meteorological conditions and other circumstances causing low-level windshear, including windflow around obstacles (refer *Section 3.2* of the Manual). *Sub-section 3.2.2* specifically mentions windshear caused by large buildings located near runways.

Section 3.7 contains valuable data providing an indication of the statistics of low-level windshear in the vicinity of aerodromes, including a study involving 10,000 landings by KLM B747s and over 9,000 landings by BA B474s. **Attachment B** includes a Figure B2, showing probabilities of exceeding for given windshear values, all of which are applicable to Schiphol Airport – of specific interest to the present SLR study.

Section B3 Aviation Industry Response to Windshear Risk

Section B3 describes the evolution of the various airport detection systems termed Low Level Windshear Alert Systems (LLWAS), developed in response to the windshear threat at airports. More recently, the US Federal Aviation Administration (FAA) began deploying two new wind shear detection systems: the Terminal Doppler Weather Radar (TDWR) and the third-generation Low Level Windshear Alert System (LLWAS 3).

Section B4 The Australian Experience

This section examines the information gap existing in Australia in relation to weather-related incidents and some key historical studies examining the incidence of windshear around Australian airports.

Section B4 Australian Case Studies

This section examines four Case Studies involving windshear and turbulence at Australian airports.

Section B5 UK Case Studies

The reader is referred to the detailed analysis of aviation accidents/incidents documented in UK Air Accident Branch (AAIB) Bulletins, including numerous windshear-related accidents.

3.1 Section 3 Synopsis

As more comprehensive weather monitoring systems became prevalent in the 1960's and 1970's, a growing awareness of the "signature" and frequency of windshear events (especially in the US) led to a better understanding of their influence on aviation accidents/incidents.

It is clear that weather continues to play a significant role in terms of all aviation accidents/incidents and that windshear and turbulence make up a significant percentage of those weather-related aviation accidents/incidents. While icing is a significant factor in upper latitudes (as evidenced by US aviation accident/incident statistics), windshear and turbulence are present everywhere.

Current best estimates indicate that, since 1943, the total number of (commercial flight) windshear and/or downdraught accident deaths is **over 1,400** (including all classes of aircraft, not just large transport aircraft).

Aviation incident investigations and reports are a valuable source of information regarding the severity of windshear which results in an impact to an aircraft's intended flight path such that significant action, including control input, is required to correct it.

4 EVIDENCE FOR BUILDING-INDUCED WINDSHEAR EVENTS

4.1 Australian Case Studies

Case 1 Canberra Airport 05/11/2002 Boeing 737

The extracts below have been taken from the ATSB (**Australia Transport Safety Bureau**) Final Investigation Report into an incident involving a Boeing 737 which occurred at Canberra Airport at 1718 hours (EST) on 5 November 2002.

The Incident

At 1718 EST on 5 November 2002, VH-TJG, a Boeing 737-476 aircraft, encountered turbulence 1718 ESuT during the landing flare on runway 35 at Canberra International Airport. The aircraft was operating a scheduled fare-paying passenger service from Melbourne, Victoria to Canberra, ACT. The pilot in command was the handling pilot for the flight.

At 1700, the wind direction and speed at Canberra was 280 degrees TN at 18 kts, gusting to 23 kts. At 1730, it was 280 degrees TN at 18 kts, gusting to 26 kts. Runway 35 was aligned on magnetic heading 348 degrees, which was equivalent to 360 degrees TN.

The automatic terminal information service (ATIS) at Canberra airport provided information on the prevailing weather conditions. At the time of the occurrence, information "Sierra" was current. It included information that runway 35 was in use, and that the wind direction and speed was 270 degrees MN, with a minimum speed of 15 kts and maximum speed of 25 kts.

The aircraft was equipped with a solid-state digital flight data recorder (SSFDR). The flight data plots revealed that the pilot in command applied left control wheel to achieve a left wing low attitude of about 3 degrees as the aircraft descended through a radio altitude of about 60 ft. At about 6 ft radio altitude, the aircraft suddenly rolled left to a left wing low attitude of about 6 degrees, and the pilot in command rapidly applied right control wheel input to arrest the roll to the left. The aircraft landed about one second later in a slightly right wing low attitude. The landing was completed without further incident, and there were no reported injuries to any of the 34 occupants of the aircraft.

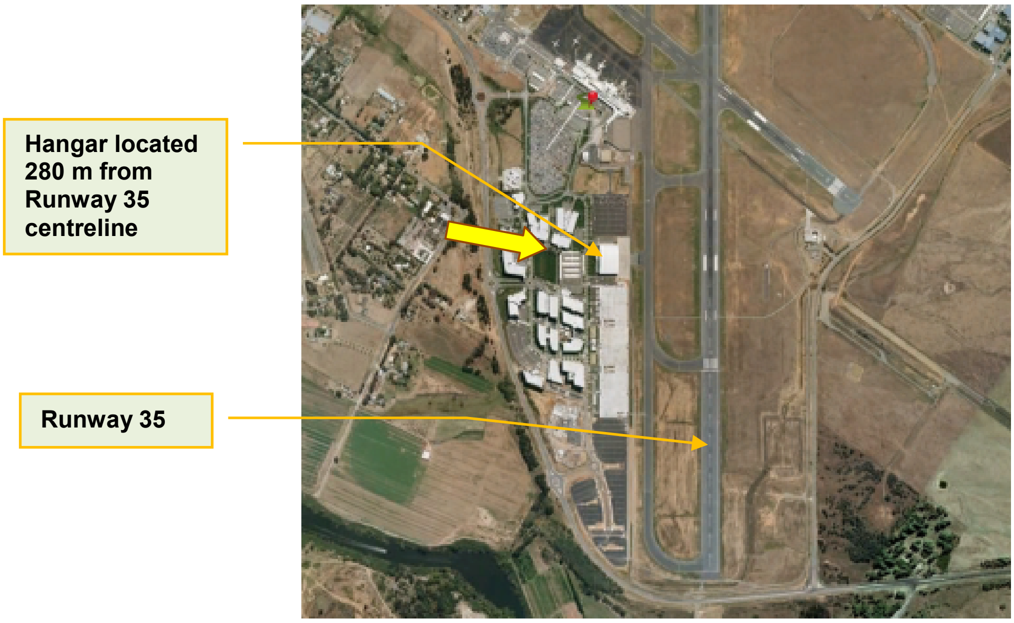
Possible Explanation

The pilot in command subsequently reported that the **turbulence encountered during the landing flare appeared to have resulted from a hangar** located adjacent to, and to the west of, the touchdown zone of runway 35.

Construction of the hangar was completed in April 2002. The roof height on the airside face of the hangar is 21.7 m and the airside (eastern) face of the hangar is located approximately 280 m from the centreline of runway 35, ie 13 building heights distance from the runway.

At the time of the occurrence, the wind direction and speed at Canberra aerodrome was 280 degrees TN at 18 kts, with gusts exceeding 20 kts at times. The wind direction was therefore 80 degrees removed from the runway direction, providing a left crosswind of about 18 knots. It is therefore possible that the prevailing wind conditions at the time of the occurrence resulted in turbulent downwind wake eddies from the hangar located adjacent to, and to the west of, the touchdown zone of runway 35.

Figure 16 Canberra Airport – Runway 35 (southern end) and Nearby Hangar



Outcomes of the Incident

Following the November 2002 Canberra incident, the following safety actions were initiated:

- The operator of Canberra International Airport requested Airservices Australia to include a caution note in Canberra aerodrome information contained in the ERSA, as follows:

  `During strong westerly winds down stream of buildings, severe turbulence may be experienced in the touch down area while landing Runway 35.'

- The operator also requested Airservices Australia to issue a Notice to Airmen (NOTAM) to reflect that cautionary advice until the ERSA was amended, and to give consideration to making:

  `…necessary caution announcements on the ATIS during similar strong wind conditions.'

Airservices Australia issued a local instruction to air traffic controllers at Canberra Tower. The instruction contained information that when the crosswind component (including gusts) from the west equals or exceeds 12 kts and runway 35 or 17 is nominated, the following shall be included on the ATIS:

`Expect turbulence over runway south of runway intersection.'

The instruction included information that controllers were to make a directed broadcast to aircraft operating on runway 35, or departing runway 17, when this crosswind condition exists and runway 35 or 17 were not nominated on the ATIS. Airservices reported that it did not consider the issue of a NOTAM providing cautionary advice of turbulence was warranted, as directed broadcasts would provide pilots with information of the meteorological phenomenon. Airservices Australia also reported that it would conduct a survey of the turbulence phenomenon until 1 July 2003 to determine the extent of the condition, including:

- occasions when the westerly crosswind component, including gusts, was ≥12 kts,
- pilot reports of turbulence / shear at touch down or take-off, including aircraft type,
- pilot comments, and
- pilot reports of turbulence when the crosswind is less than 12 kts.

Case 2 Canberra Airport 31/01/2010 Grumman Traveller AA-5

The extracts below have been taken from the ATSB (**Australia Transport Safety Bureau**) Aviation Occurrence Investigation Report AO-2010-008 (Final, April 2011) into an incident involving a Grumman Gtraveller AA-5 which occurred at Canberra Airport at 1630 hours (EST) on 31 January 2010.

The Incident

At 1630 EST on 31 January 2010, VH-ERP, a Grumman Traveller AA-5 aircraft, encountered severe turbulence during final approach on runway 12 at Canberra International Airport. At an altitude of about 150 ft AGL, the aircraft experienced severe turbulence that resulted in a brief loss of control. The pilot recovered control and landed on runway 12.

On 31 January 2010, VH-ERP was being operating between Temora (NSW) and Canberra under visual flight rules. Runway 35 was in use at the estimated time of arrival of the flight; the wind direction and speed at Canberra was 020 degrees MN at 10 kts.

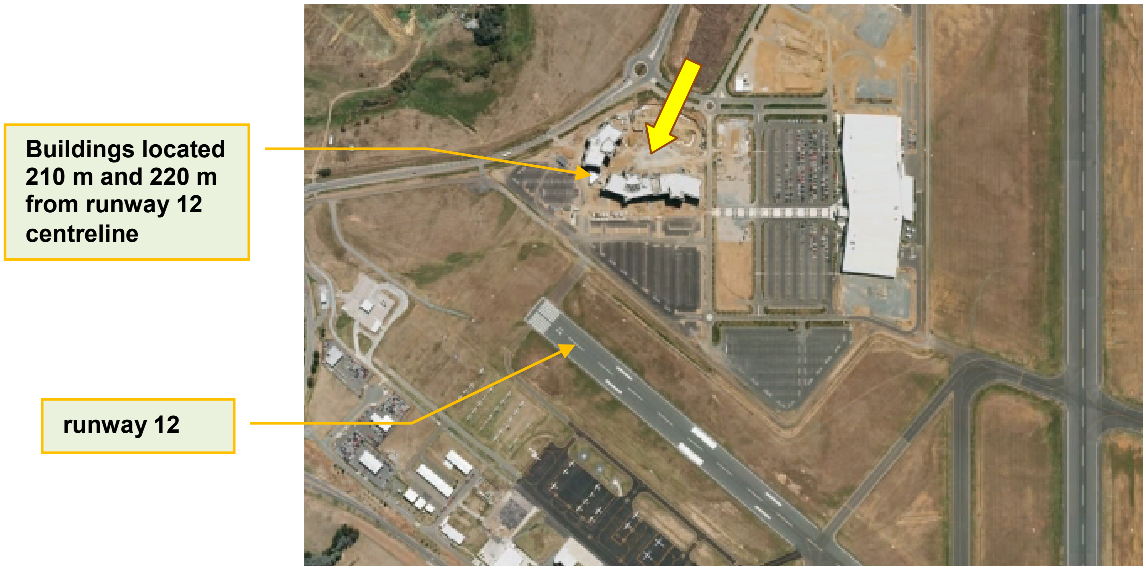
There were other aircraft ahead of VH-ERP in the sequence for runway 35. Canberra airport ATC considered runway 12 suitable for use and the aerodrome's controller offered ERP's pilot the option oifusing runway 12 for landing. The pilot accepted runway 12, as the reported crosswind of 10 knots was within the aircraft's operating limitations.

At 1630 EST, VH-ERP was just past the runway 12 threshold markings on approach and at an altitude of about 150 ft AGL. The aircraft then suddenly encountered severe turbulence which resulted in an uncommanded roll to the right of about 60º from the horizontal. The pilot responded with an immediate full left aileron and was able to restore control; the aircraft landed safely, slightly past the marked touchdown zone

Postulated Explanation

The conclusions of this incident suggest that the wind disturbance encountered by VH-ERP on final approach was caused by a combination of wind conditions on the day and turbulence generated by two airport buildings located just over 200 m upwind from runway 12. These buildings are positioned such that they would interrupt wind north to northewast winds impacting on the approach and landing areas of runway 12.

Figure 17 Canberra Airport – Runway 12 and Nearby Buildings



The buildings of interest are part of the Majura Park precinct and were constructed in 2008. They are 20 m to 25 m in height and hence of the order of 10 building heights distance from the runway.

Outcomes of the Incident

In 2007, two independent wind studies were commissioned by the aerodrome to assess the potential impact of the planned developments in the Majura Park precinct, including the two buildings of interest. These "desktop" studies utilised an acceptability criterion based on building turbulence being a potential issue up to 10 building heights downstream of the structures of interest. The basis for the adoption of this criterion is unknown.

These studies acknowledged that the buildings of interest were close to this assumed 1:10 threshold distance criterion. However it was felt that aircraft operations should not be affected, given that runway 12 would not likely be used under northerly wind conditions and, in any case, north to northeast sector winds were relatively moderate.

The 2002 B737 incident described in Australian Case Study 1 resulted in the aerodrome operator requesting Airservices Australia to include a caution note in Canberra aerodrome information contained in the ERSA, as follows:

> *During strong westerly winds down stream of buildings, severe turbulence may be experienced in the touch down area while landing Runway 35.*

No similar caution note has been issued (at this time) for operations to/from runway 12.

4.2 UK Case Studies

Ref: UK AAIB Bulletin No. 11/1998

Case UK1 London Heathrow Airport 05/04/1998 - 0957 hrs Boeing 747-400

The Boeing 747-400 was departing from Heathrow's Runway 27L on a scheduled passenger flight to Kuala Lumpur. The crew recorded the pre-departure weather as a surface wind from 200°MN at 19 kt, with a dry runway state. With the surface wind conditions, the crew calculated that the aircraft would have a 6 kt headwind component and an 18 kt crosswind component for takeoff. The aircraft's Operations Manual indicated that the maximum permitted crosswind component for takeoff from a dry runway was 30 kt (with gusting to 35 kt).

The Tower controller passed the surface wind as 210°MN at 15 kt at the time takeoff clearance was issued. The take off commenced at 0957 hrs. During the take-off acceleration, the commander noted that the airspeed indication (speed tape and trend vector arrow displays on the Electronic Attitude Director Indicator) was fluctuating at around 10 kt and at V1. The rotation was commenced at VR, but the commander perceived that the speed increased towards V2+20 kt as the rotation continued. In order to assist the first officer in achieving the correct speed for the initial climb, the commander made an additional rearward control column input. This caused the aircraft to pitch up at an increased rate and the tail of the aircraft struck the runway as the aircraft left the ground. The stick shaker activated momentarily and a forward control column input was made to reduce the pitch attitude.

The aircraft continued to climb away, with the first officer adjusting the pitch attitude to the correct climb attitude. The landing gear was not retracted until the flight path had stabilised and the aircraft was passing about 1,000 ft AGL. ATC informed the aircraft that some debris had been observed falling from the tail section. The aircraft was depressurised in accordance with the requirements of the Tail Strike procedure and the commander decided to jettison fuel before returning to land at Heathrow.

ATIS information code 'Kilo' was broadcast from 0908 hrs until 0931 hrs. This indicated a surface wind of 200° at 15 kt, variable between 160° and 230°. This was used by the crew for takeoff performance planning purposes. Updated information code 'Lima' was broadcast from 0931 hrs to 0957 hrs. This indicated a surface wind of 200° at 16 kt, variable between 160° and 230°. Further updated information code 'Mike' was broadcast from 0957 hrs (the takeoff time), indicating a surface wind of 200° at 16 kt, minimum 11 kt, maximum 26 kt, variable between 170° and 230° with the present weather being a rain shower.

Anemograph recordings were available from an anemometer located at the southwest corner of the airport and a second anemometer located at the northeast corner of the airport. At the time of the accident, these showed a variation in direction from 200° to 230° at the southwest anemometer and from 170° to 250° for the north east anemometer. The wind speed variations were between 9 kt and 24 kt at the southwest anemometer and between 12 kt and 24 kt at the north east anemometer.

Influence of the World Cargo Centre on wind velocity over Runway 27L

Prior to the construction of the World Cargo Centre building to the south of Runway 27L at Heathrow, wind tunnel testing was carried out to evaluate the effects of the presence of the building on the wind velocity over Runway 27L. For the ambient wind conditions at the time of this accident, the measured effect of the presence of the building was to produce a slight decrease of about 2 kt in wind speed (crosswind and headwind components) at a position some 1,700 m from the start of the takeoff run for Runway 27L. At around 1,800 m from the start, there was then an increase in the wind speeds, some 2 kt headwind and 4 kt crosswind component.

It is not considered that these changes alone would have produced a significant effect on the takeoff handling or performance in this case.

UK AIP Warning for London’s Heathrow Airport (LHR)

The UK Aeronautical Information Publication (AIP) contains the following warnings for LHR:

> *“Pilots are warned, when landing on Runway 27R in strong southerly / southwesterly winds, of the possibility of building-induced turbulence and large windshear effects."*

Also:

> *"Similarly, R27L arrivals may be affected by winds with a strong northerly component. Building-induced turbulence may be experienced at the mid sections of each runway from winds with a strong southerly, or strong northerly component."*

As noted above, a study of wind effects was carried out on Runway 27L in 1995 prior to the construction of the new cargo building some 450 m from the runway. No study has been undertaken for the environment around Runway 27R and so no data comparison is possible here.

Ref: UK AAIB Bulletin No. 6/2002

Case UK2 Goodwood Aerodrome 31/01/2002 - 0945 hrs CASA 1-131E

The aircraft departed Goodwood for a local flight returning to the aerodrome for some circuits and practise forced landings. Weather conditions were good with a surface wind from the southwest of 10 kt for departure, although this increased to about 18 kt by the time the aircraft returned.

Various circuits were flown using runway 24 without incident, and on the final circuit it was intended to complete another practise forced landing. The aircraft climbed to a height of 1,200 ft and the power reduced to idle on the downwind leg to runway 24.

Initially the approach angle, airspeed and rate of descent were all appropriate and the aircraft crossed the threshold with a small amount of sideslip applied. It was reported that at a height of approximately 50-60 ft above the runway there was a significant increase in the sink rate which the handling pilot attempted to counter by applying full power. Despite this action the aircraft made a hard landing, measured on the aircraft's accelerometer as 4g. The aircraft bounced and a go-around was initiated. During the ensuing circuit, it was noticed that the landing wires on the port wing looked stretched and bent although a safe landing was accomplished.

The handling pilot considered that he may have encountered an area of windshear, and commented that the wind direction meant that the airflow over the runway may have been disturbed by some nearby hangars. He also stated that other pilots, including flying instructors, had encountered similar windshear during that morning.

Ref: UK AAIB Bulletin No. 8/2005

Case UK3 London City Airport (LCA) 29/11/2004 - 0914 hrs DHC-8-311 Dash 8

The aircraft and crew were engaged on their second of four sectors for that day from the Isle of Man to London City Airport (LCY). After an uneventful cruise, the first officer flew an ILS approach to runway 10. The 5.5º glide path was intercepted from an altitude of 2,000 ft and manually flown with landing flap (15º) set. At 430 ft, the speed was VREF +17 kt (108 kt). On taking control, the commander progressively reduced engine power and achieved VREF +5 kt before entering the flare. He maintained the 5.5º glide path using the precision approach position indicators (PAPIs) but on entering the flare reported heavy 'sink'. As the commander pulled back on the control column, the nose of the aircraft rose rapidly and the first officer called "six degrees pitch" in accordance with company Standard Operating Procedures (SOPs). The 'LDG ATT SIX DEG' message was also displayed on the advisory display unit. The first officer's call was not heard by the commander and almost simultaneously a firm landing was made. During the roll out the 'TOUCHED RUNWAY' red warning light on the flight deck was observed to be illuminated.

The meteorological report for LCY at 0850 hrs described a surface wind of 360º/8 kt with good visibility and little cloud. The crew reported that there was little turbulence on the approach but suggested that a recently glazed building to the north of the runway may have induced some turbulence at their touchdown point. Other crews landing that morning did not report any turbulence but there is anecdotal evidence of turbulence when the wind is stronger from the same direction.

Effects on environmental conditions

The United Kingdom Aeronautical Information Publication (UK AIP) entry for LCY 2.20 paragraph 4 states:

> *“pilots are warned when landing on Runway 10 or Runway 28 in strong wind conditions, of the possibility of building induced turbulence and/or windshear.”*

LCY's Operations Department produced a set of Aerodrome Safeguarding Procedures in July 2004 in order to assess the effects of proposed building development on airfield operations. Paragraph 5.8, entitled Wind Assessments, states that:

> *“Any new developments proposed … should include an appropriate assessment of any potential implications the development may have by providing for unusual changes to wind conditions with regards the airfield operation at LCY following the completion of the development. These assessments should be carried by a competent authority in consultation between the developer and LCY.”*

Existing building development at LCY required no such wind assessment.

Ref: UK AAIB Bulletin No. 6/2002

Case UK4 London Gatwick Airport (LGA) 01/02/2002 - 2230 hrs Airbus A300

The aircraft was operating an empty positioning flight from Manchester Airport to London Gatwick Airport. The aircraft made an ILS approach to runway 26L at Gatwick. The crew reported that flight conditions were turbulent. At about 1,000 ft, the commander recalled noticing an IRS (Inertial Reference System) wind speed readout of 70 kt. The crew recalled that the reported surface wind was from 210° at 18 kt with gusts to 30 kt shortly before landing. The pilot flying began to flare the aircraft, but then experienced a left wing drop. He attempted to correct this by application of right aileron and additional power. However, the aircraft touched down heavily, first on the left main gear, followed by the right main gear. The aircraft rebounded into the air and, following a nose down elevator input, touched down in a nose down pitch attitude with right roll. The right main gear, nose landing gear and right engine contacted the runway surface. The aircraft completed two more brief bounces during the landing roll. The subsequent hard landing inspection showed damage to the underside of the cowling of the right engine.

The Flight Data Recorder indicated that there was a reduction in airspeed of about 10 kt just before touchdown. The recorded peak vertical acceleration sustained was 1.96 g, which occurred on the first touchdown. The peak vertical acceleration was 1.46 g for the second touchdown, with the aircraft at 2.5° nose down pitch attitude and 11.25° right roll attitude, at which time the engine cowling contacted the runway. The peak vertical acceleration for the third touchdown was 1.54 g. The nose down pitch attitude of the aircraft appeared to have resulted from a forward control column input.

The manufacturer's maximum computed and demonstrated crosswind for the aircraft is 32 kt. This was the figure adopted by the operator for the A300 fleet crosswind limit. The manufacturer's computations and demonstrations of crosswind performance assumed a steady state crosswind.

Effects on environmental conditions

The United Kingdom Aeronautical Information Publication entry for London Gatwick Airport contains the following warning:

> *"Pilots are warned, when landing on Runway 26L/R in strong southerly/southwesterly winds, of the possibility of building induced turbulence and windshear effects.'*

4.3 Hong Kong Case Studies

Ref: Chan, Lo & Leung (2010)
"Low Level Wind Effects of the Hangars at the Hong Kong International Airport)

This paper examined instances where significant differences were recorded between winds at the anemometers located at the western end of Hong Kong International Airport (HKIA). Using CFD simulation and comparing to actual strong wind events (including the passage of a tropical cyclone in 2008), the influence of the hangars located between the two main HKIA runways was shown to be a factor in these wind speed variations. The wind predictions were also compared to wind recorded on board landing aircraft and concurrent pilot reports of the winds experienced during landing.

Figure 41 shows the western end of the airport, the two main runways and the hangar buildings of interest.

The influence of local topography on wind speeds in the vicinity of HKIA has been well documented, in particular the impact of the mountainous terrain of Lantau Island located south of the airport. There has also been a suggestion that building-induced windshear may be present at the airport as well.

Figure 18 HKIA Western Precinct

One such instance occurred during the passage of Typhoon Nuri past the airport on 23 August 2008 during which time, strong north-northwesterly winds were impacting the local area. There are two anemometers at the western ends of the north and south main runways. During mid-morning that day, the sustained winds recorded at these two anemometers varied by up to 5 m/sec. Two aircraft which arrived at 10:30am and 10:50am reported “hard” landings. The pilot report from one of these stated that the plane appeared to “drop out of the sky” just before landing, experiencing flipping to the right shortly after landing and passing by the hangars to its left.

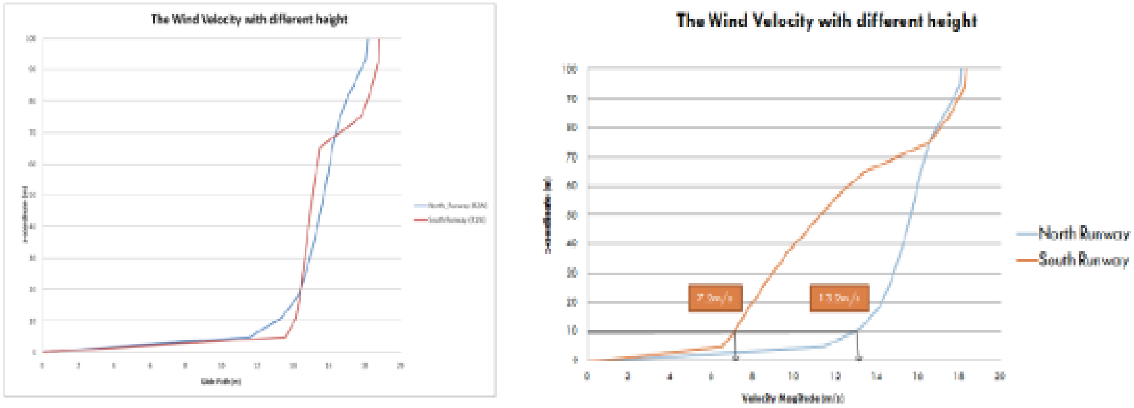
In this study, CFD was used to simulate the wind profiles at the anemometer locations and on the south runway area where landings of interest took place on 23 August 2008. The CFD results were then compared to the actual anemometer records as well as in-flight wind recordings.

The following presents a selection of results taken from this study.

Figure 19 shows the predicted wind profile (with height) for the CFD model with and without the hangar buildings of interest.

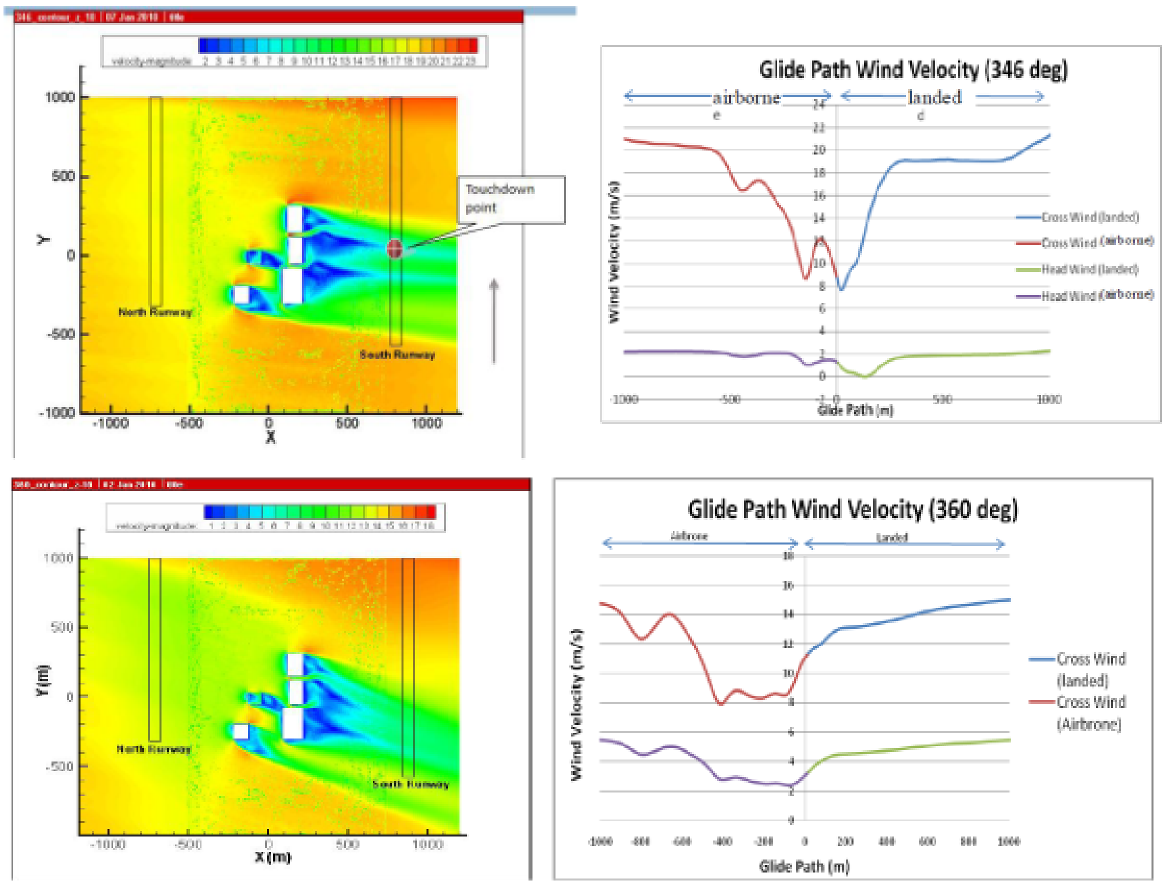
Figure 20 shows surface wind contours for two wind approach angles of interest indicating the horizontal windshear conditions likely to be present under the same meteorological conditions on 23 August 2008. These simulations were in good agreement with the actual wind recordings from the airports anemometers and the in-flight recordings made on the day by aircraft landing on the southern runway at HKIA.

Figure 19 HKIA Simulated Wind Profiles With/Without Nearby Hangar Buildings



No Hangars **Hangars Present**

Figure 20 CFD Simulations Indicating Potential Windshear Effect of Hangars



(a) (b)

The simulation results and comparison with anemometer and aircraft data in this study show that the hangars between the two runways of HKIA have the potential to significantly influence crosswind conditions for the airport's southern runway under adverse approach wind conditions.

4.4 Section 4 Synopsis

As can be seen from the extent of case studies included in **Section 6**, there have only been a relatively small number of aviation accidents/incidents where sufficient information exists to be able to establish (with confidence) that building-induced wake effects was the likely cause.

This is understandable given the conditions required for potentially hazardous building-induced accidents/incidents to occur. As has been described, the "ideal, worst-case" conditions would involve a simultaneous combination of the following:

The ambient windflow would need to be close to perpendicular to a runway.

Accordingly, there would have to have been strong reasons for the pilot of an aircraft as well as control tower staff to agree to use the runway under crosswind conditions, as opposed to another runway where headwind/tailwind conditions would be encountered.

Overall wind conditions would likely involve "clear" skies with low (upstream) turbulence suggesting manageable risk conditions to both pilots and control tower staff.

A building would need to be located in sufficiently close proximity to the end of the runway of interest so that its wake could overlap the critical landing / takeoff area for normal flight operations.

The building of concern would need to have dimensions conducive to the creation of a large wake: reasonable overall size; W/H > 1 for rectangular buildings so no re-attachment; the possibility of oblique flows creating long-lasting delta-vortices; unusual shape, etc.

The occurrence of building-induced windshear would therefore be less likely than windshear arising from other phenomena (eg microburst, gust front, etc) which can impact any runway at any time.

Several factors suggest that the frequency of occurrence of building-induced windshear may well increase in the future:

- Simulation tools such as CFD (computer-based) and wind tunnel (scaled model-based) are now available to quantify the downwind impact of building wakes both in terms of mean winds and turbulence levels. This understanding is bound to raise the awareness of the phenomenon.
- The incentive for private airport operators around the world to maximise the potential of the seemingly large areas of available land on their premises is likely to continue into the future.
- Increasing passenger loads and the move towards larger aircraft usage (which have the "perception" of being able to cope with more difficult windflow circumstances) will probably increase the likelihood of aircraft using runways under strong crosswind conditions.

In summary, building-induced windshear is "real" but has not occurred as frequently as other forms of windshear. However, its frequency is likely to rise in the future.

5 AVIATION INDUSTRY RESPONSE (BEST PRACTICE) TO WINDSHEAR

The term windshear can be used to define any change of wind speed (magnitude) and/or wind direction, occurring in either a horizontal or vertical sense. Windshear applies equally to changes in sustained speeds and is thus differentiated from turbulence which describes the local fluctuating component of the wind above and below the local mean wind present at that time.

Aircraft are not ordinarily bothered by modest changes in either wind speed or wind direction, especially when they are flying at altitude. Similarly, aircraft are not ordinarily bothered by larger changes in either wind speed or wind direction when those changes take place over a long period of time.

Consequently, in so far as aviation safety is concerned, windshear is taken to infer an abrupt change in wind of sufficient impact (by virtue of magnitude and/or direction change) as to have the potential to affect the performance of an aircraft so significantly that it challenges the compensation capabilities of the pilot and the aircraft.

This introduces two further considerations in terms of establishing threshold criteria relevant to windshear events of concern:

- Such criteria will depend on the capabilities of the specific aircraft type; and
- Such criteria will depend on the flight situation – for example, an aircraft cruising at altitude has options to sustain altitude changes in response to airspeed anomalies which are simply not available to an aircraft in the final approach of landing or at the point of take-off.

A definition of windshear which captures the above characteristics is shown below, extracted from UK AIC (Aeronautical Information Circular) 84/2008 (Pink 150, September 2008) "*Low Altitude Windshear*"

2.2 The definitions of windshear used in this circular are:

(a) Windshear:

Variations in the wind vector along the flight path of an aircraft with a pattern, intensity and duration that will displace an aircraft **abruptly** from its intended flight path such that **substantial control input and action is required** to correct it.

(b) Low altitude windshear:

Windshear along the final approach path or along the runway and along the take-off and initial climb-out flight paths.

5.1 Quantification of Hazardous Levels of Windshear – Early Studies

Attempts to establish hazardous levels of windshear can be found in seminal studies of weather phenomena containing windshear (such as gust fronts and microbursts) and their impact on aviation (especially during take-offs and landings) – for example Fujita et al (1997) and McCarthy (1997). The following seems to have emerged as a consensus regarding windshear levels of concern:

- Moderate windshear: A 10 m/s head/tail-wind loss or gain over a distance of 1-4 km
- Severe windshear: A 15 m/s or greater head/tail-wind loss or gain over a distance of 1-4 km

A parallel series of turbulence level thresholds of concern also emerged, based on the cube root of the turbulent EDR (eddy dissipation rate) value – refer **Section 2**.

- Moderate turbulence: An $\text{EDR}^{\wedge 1/3}$ of at least 0.2
- Severe turbulence: An $\text{EDR}^{\wedge 1/3}$ of at least 0.4

On the basis of the frequency of occurrence of meteorological observations made near airports and studies of correlation with aviation incidents, it appeared from these studies that the incidence of moderate-to-severe windshear events was considerably higher than the incidence of moderate-to-severe turbulence.

5.2 Hong Kong

The windshear alert criteria used in Hong Kong are of particular interest given the sophisticated windshear monitoring system which has been installed at Hong Kong International Airport (HKIA). At HKIA, windshear alerts are based on changes to alongwind conditions (ie in line with the flight path):

- A sustained change in headwind (or tailwind) of 15 knots or more at a height of 1,600 ft or below

HKIA also issues microburst alerts when a sustained change in headwind (or tailwind) of greater than 30 knots occurs at a height of 1,600 ft or below.

In the past, the airport also used various anemometer-based crosswind rules (ie for winds perpendicular to the flight path) involving the exceedance of a 1-minute mean crosswind component (relative to the runway orientation) above a given threshold. Different numerical thresholds however had to be developed depending upon the specific anemometer chosen for reference - HKIA has access to numerous anemometers, some at the airport itself, some over water (weather buoys) and others located on surrounding topographical features, eg elevated locations on Lantau Island.

HKIA also issues turbulence alerts based on the value of the cube root of the EDR (eddy dissipation rate – refer **Section 2**).

- Moderate turbulence alert: An $EDR^{1/3}$ of at least 0.3
- Severe turbulence alert: An $EDR^{1/3}$ of at least 0.5

5.3 FSF ALAR Windshear Briefing Note

Windshear information is provided in the following Flight Safety Foundation (FSF) publication:

**Ref: FSF ALAR (Approach-and-Landing Accident Reduction) Tool Kit
"Briefing Note 5.4 – Wind Shear".**

The FSF's Approach-and-Landing Accident Reduction (ALAR) Task Force states that wind conditions (including windshear) were involved in about 33% of 76 approach-and-landing accident and serious incidents worldwide in the period 1984-1997 – refer FSF publication *"Killers in Aviation: FSF Task Force Presents Facts About Approach-and-Landing and Controlled-Flight-into-Terrain Accidents"* (1999).

Accordingly, various weather-related guidance materials were developed by FSF including the above tool kit covering windshear. It was assumed that aerodromes and pilots would have access to the information created (in the US) by the Low Level Windshear Alert System (LLWAS).

The FSF ALAR briefing note makes the following recommendations:

- A windshear alert should be issued whenever a difference in reported/measured winds in excess of 15 knots is detected.
- Pilot reports (PIREPS) of windshear causing airspeed fluctuations in excess of 20 knots or vertical speed changes in excess of 500 ft/min when below 1,000 ft AGL should be cause for concern.
- In addition to the above, indications of suspected windshear include: pitch altitude excursions of 5º or more; heading variations of 10 º or more; glideslope deviations of one dot or more; unusual autothrottle or throttle lever position.

5.4 ICAO (International Civil Aviation Organisation)

As noted in **Section 3** provisions for international civil aviation are adopted by the International Civil Aviation Organization (ICAO) - a body of the United Nations headquartered in Montréal. These provisions are located in 18 annexes; Annex 3 describes the meteorological service for international air navigation and corresponding international standards and recommended practices.

One topic, windshear warnings (section 7.4), references the Manual on Low-level Wind Shear and Turbulence (ICAO Reference 9817) as a guide on the subject of windshear. This replaced the previous guidance document, Circular on Wind Shear, published in 1987.

Ref: ICAO, 2005:
"Manual on Low-Level Wind Shear and Turbulence".

The ICAO's guidance criteria for the incidence of a windshear or microburst event of concern are primarily related to weather-induced phenomena:

- Windshear: A head/tail-wind loss or gain of at least 30 km/hr (15 knots) over 4 km
- Microburst: A head/tail-wind loss or gain of at least 60 km/hr (30 knots) over 4 km

5.5 UK AIC Guidance

Windshear information can be found in the following UK AIC (Aeronautical Information Circular) publications:

Ref: UK AIC 84/2008 (Pink 150, September 2008):
"Low Altitude Windshear".

UK AIC P056/2010 (August 2010):
"The Effects of Thunderstorms and Associated Turbulence on Aircraft Operations".

The above AIC guidance documents note that, in the UK, windshear warnings are provided in ATIS broadcasts at London (Heathrow) and Belfast (Aldergrove) if the following conditions exist:

- The mean surface wind exceeds 20 knots;
- The vector difference between the mean surface wind and the gradient wind at about 2000 ft exceeds 40 knots;
- Thunderstorms or heavy showers are within about 5 nm of the airfields.

The above AIC guidance documents also observe that, as would have become obvious in this Section, there is no universal standard (internationally) regarding the grading of the severity of windshear, nor is there a universal standard regarding windshear warnings.

5.6 The Amsterdam Schiphol Airport "7-knot" Criterion

The influence of buildings on airport windshear conditions became the focus of a number of studies conducted by scientists and researchers in The Netherlands due to the perceived impact of an engine test run facility for wide body aircraft located just to the south (~300 m) and at the eastern end of Amsterdam's Schiphol Airport runway 27 – refer **Figure 21**. The U-shaped facility has a representative width in relation to the runway of approximately 120 m.

A number of pilots reported wind-related disturbances when using runway 27 under strong southwest wind conditions. Subsequent studies determined that the primary cause was the wake behind this facility and the corresponding variation in crosswind experienced by aircraft using this runway during their last stage of approach.

Using pilot reports, wind tunnel tests and flight simulator tests, NLR developed a simple-to-use criterion (first nominated in Krus et al, 2003) for advising of the potential for adverse building-induced windshear, **BI-Wsh**, the so-called "*7 knots criterion*", related to the maximum allowable lateral wind speed deficit occurring behind an obstacle:

Figure 21 Amsterdam Schiphol Airport's Engine Test Bay (near the end of runway 27)

The so-called ***"7-knots criterion"*** was given further status via a follow-up study by Nieuwpoort at al (2006) based on flight simulations. The **BI-Wsh** rule developed through these studies was related to the maximum allowable lateral wind speed deficit occurring behind an obstacle:

- "*The difference in wind velocity **perpendicular** to the aircraft over a **short distance** may not exceed **7 knots***"

In practice, the criterion was applied by requiring all building developments protruding an imaginary plane with a slope of **1 to 35** to undergo further (detailed) investigation.

5.7 The Amsterdam Schiphol Airport 2008 Study

The "7-knot criterion" was updated in a far-reaching study carried out in 2008:

Nieupoort, Gooden & de Pins
"Wind criteria due to obstacles at and around airports"
Report NLR-CR-2006-261, May 2008 (National Aerospace Laboratory of The Netherlands)

This study is the most in-depth study of the influence of airport buildings and other bluff structures on aviation-related windshear. This report focussed on developing wind disturbance criteria relevant to wake effects induced by "obstacles" (eg buildings, walls, etc) at airports, particularly during the final stages of approaches when aircraft are most vulnerable to such effects.

The report distinguished associated risk levels with three altitude bands: 0 ft to 200 ft, 200 ft to 1,000 ft and >1,000 ft. Only the **first (lowest) altitude band** was deemed to pose a potential critical risk to aircraft safety.

The approach used to develop the wind disturbance criteria employed a unique methodology using offline mathematical flight performance simulations with two aircraft types – a B747 and a Fokker 100 – chosen because these were two planes at the high and low end of aviation weight and inertia ranges. The conclusions of the 2008 study are as follows:

Altitude Range: 1,000 ft AGL to 200 ft AGL

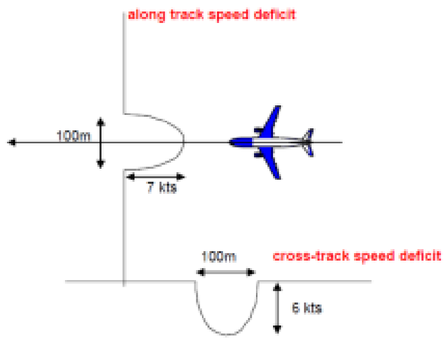
- For the approach flight phase covering an altitude range of 1,000 ft AGL to 200 ft AGL, the **ICAO's obstacle clearance planes** Annex 14) give **sufficient protection** to wind disturbances due to "stand-alone" obstacles. In this altitude range the wake effects induced by buildings and other airport "obstacles" are submerged within the ambient wind characteristics.

Altitude Range: Below 200 ft AGL

- For the final landing phase covering an altitude range of below 200 ft AGL, the study recommended wind disturbance criteria **more stringent** than the "Annex 14" planes.

The wind disturbance trigger criteria for the glide path segments of concern (ie below 200 ft) were to impose the following limits on structures located in the vicinity of airport operations:

- Along the aircraft trajectory:
  - The structure should not induce a change in mean wind speed greater than 7 knots, with the speed change taking place over a distance of at least 100 m.
- Across the aircraft trajectory:
  - The structure should not induce a change in mean wind speed greater than 6 knots, with the speed change taking place over a distance of at least 100 m.



In addition to the mean wind speed deficit criteria described above, the study developed an additional turbulence (gust) criteria:

- The horizontal gust/turbulence levels caused by a stand-alone obstacle in combination with the meso-scale surface roughness must remain below an RMS (standard deviation) value of 4 knots.

Some Additional Observations from the NLR Report

The various simulations that led to the above criteria showed that a pilot's acceptance of the disturbance caused by building wake effects was significantly influenced by the prevailing turbulence levels (ie the turbulence caused by the surrounding terrain, other buildings, trees, etc).

Atmospheric (ie non-building-induced) turbulence levels correlate with surface roughness and this varies considerably around many airports. For airports located near built-up areas, turbulence levels can quickly increase to values characterised in aviation terms as medium (~ 3 knots) to heavy (5 knots and above). Such levels can mask the impact of building-induced wake effects.

Table 2 has been extracted from the *NLR Report Table 6-9* giving the number of cases (out of 150) when unacceptable landing difficulties were encountered using F100 simulation landings. The BLUE figures are for NO building present; the RED figures are for a building present similar in dimension to the engine test bay shown in **Figure 21.**

Table 2 Extract from NLR-CR-2008-261 Table 6-9

	Ambient Wind Speed		
Terrain Type	**23 knots**	**28 knots**	**35 knots**
"Flat, Open" – low ambient turbulence	**0** **1**	**1** **4**	**1** **7**
"Rural" – increased ambient turbulence	**0** **1**	**8** **16**	**16** **18**

In the above, the figures give the number of landing difficulty exceedances out of a total of 150 simulations:

BLUE figures represent the case of a runway free of any surrounding obstacles

RED figures represent the case of a runway with the Schiphol engine bay "obstacle" building present

Table 2 suggests the following:

- At lower ambient wind speeds, landing difficulty is essentially unaffected either by an increase in ambient turbulence (rougher terrain) or by the presence of an obstacle building.

  Expressed another way, at low wind speeds, neither the ambient turbulence nor a building wake are likely to be sufficient magnitude to cause conditions involving landing difficulty.

- At higher ambient wind speeds, the effect of the obstacle building is submerged by the impact of severe (ambient) turbulence.

  Expressed another way, at high wind speeds, the ambient turbulence becomes severe enough that any additional adverse impacts from a building wake are simply not "seen".

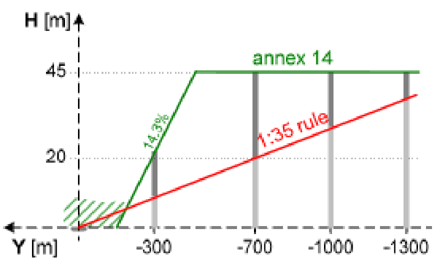
- It is in the medium ambient wind speed range that the obstacle building makes its presence felt and raises the incidence of landing difficulty by a significant amount (2-4 times).

  Expressed another way, there is a "medium" speed range, where BOTH ambient turbulence AND building wake effects have a noticeable influence on landing difficulty.

The NLR Report found a similar interaction between adverse building wake impacts and adverse ambient turbulence impacts in relation to building distance from runway. Put simply, once buildings are far enough away from the runway, their wake effects become submerged within the influence of ambient turbulence.

The NLR Report sought to translate the output of these simulation findings in relation to two standard height restriction criteria: the Schiphol 1:35 criteria and "Annex 14" level criteria, finding that:

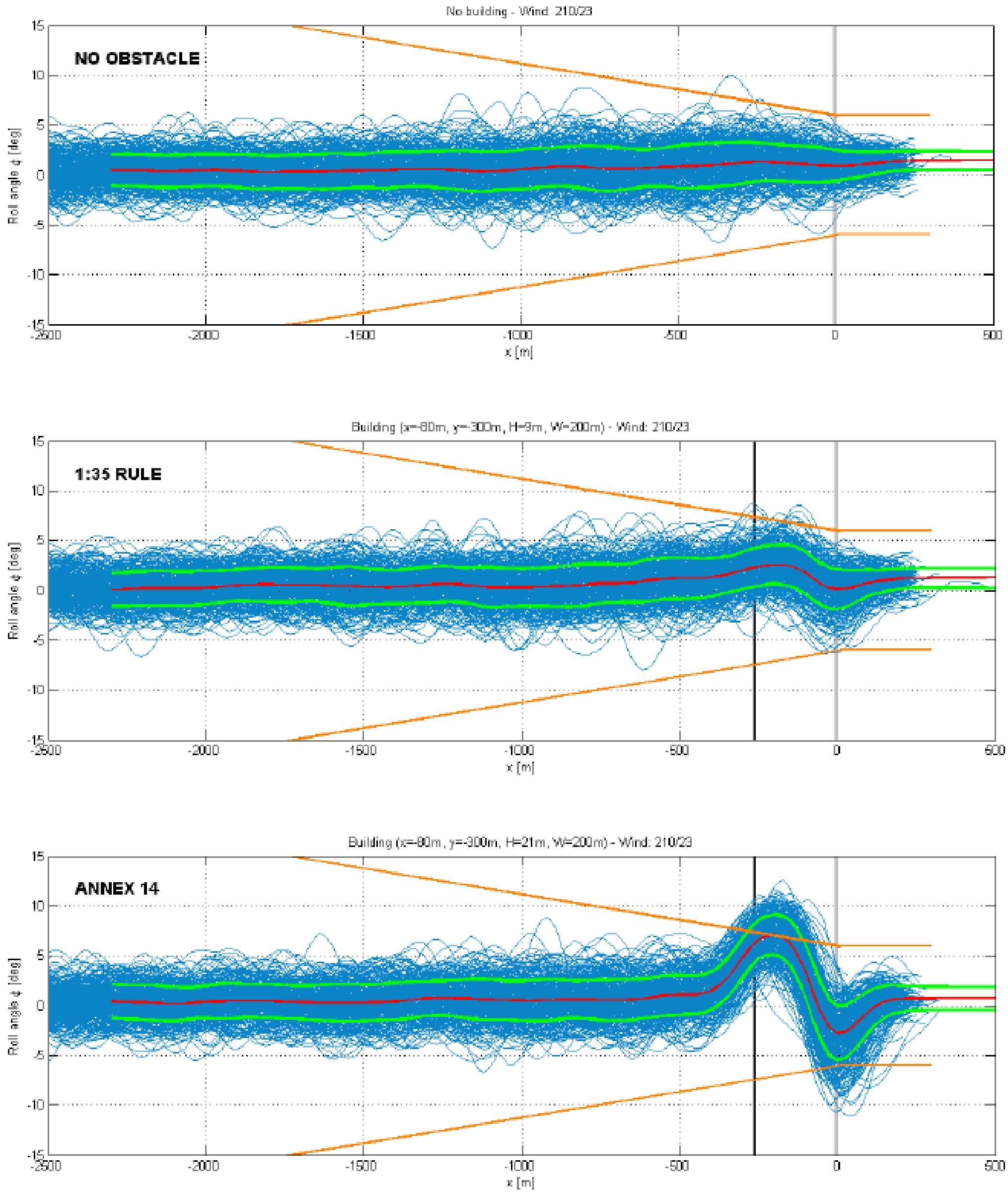
- When obstacle buildings are restricted by the 1:35 rule, their presence adjacent to a runway, at any distance, does not increase the incidence of landing difficulty relative to the ambient turbulence conditions at that airport.
- A substantial increase in the incidence of landing difficulty occurs when obstacle buildings are allowed to increase in height to the Annex 14 level. This increase becomes more pronounced as the surface roughness surrounding an airport decreases.



The above observation can be seen in the simulation results for B747 landings in terms of impact on the roll response of the airplane under three cases: No Obstacle Buildings; Obstacle Buildings within the 1:35 rule; Obstacle Buildings within the less stringent Annex 14 rule.

This is shown in **Figure 22**. The large disturbance to roll angle for the Annex 14 simulations is clearly evident in both the mean roll angles (red line) and standard deviations (green lines). The orange boundary lines show the position outside of which bank angles are considered hazardous. Clearly the highest roll angle deviations occur close to the point (refer grey vertical lines). At this point, large rolling manoeuvres at final approach and close to the ground are unacceptable.

Figure 22 Simulation Histories of Roll Angle for B747 Landings



5.8 Section 5 Synopsis

Windshear can occur in many forms, involving either horizontal or vertical changes in wind speed (magnitude) and/or wind direction. In relation to aviation safety, a windshear event of concern will normally take on additional characteristics:

- the windshear change would need to be **reasonably abrupt**
  (ie gradual changes occurring over many minutes of flight-time are unlikely to be a cause for concern to the handling pilot)
- the **magnitude** of the windshear change (in either speed or direction) must be **significant**
  (ie 1 to 2 knot change in any direction would not likely be a cause for concern)
- The windshear change would need to be **sustained**
  (ie a change experienced for a second or less would not likely be a cause for concern)
- Finally, windshear events **close to the ground**, especially at the time of final approach on landing or at take-off, are of **greater concern** than those encountered at altitude (ie say above 1,500 ft).

There is no universal standard (internationally) regarding the grading of the severity of windshear events and consequently, variations exist in the threshold criteria used for triggering windshear alerts around the world's airports.

Windshear events of concern can be specified in terms of the wind speed gain or loss in either the alongwind (in line with the flight path) or crosswind (perpendicular to the flight path) direction and usually over some minimum time period or distance.

Alongwind speed gain or loss trigger levels for windshear warnings start as low as **15 knots**.

An attempt has been made to establish a windshear trigger level specific to **BI-WS** (Building-Induced Windshear). This is the so-called "**7-knot criterion**" developed by researchers and scientists assisting operations at Amsterdam's Schiphol Airport. This criterion set a threshold limit to the crosswind component of wind encountered during landing or takeoff as follows:

> *"The difference in wind velocity **perpendicular** to the aircraft over a **short distance** may not exceed **7 knots**"*

In practice, the 7-knot criterion was applied by requiring all building developments protruding an imaginary plane with a slope of **1 in 35** to undergo further (detailed) investigation. The criterion has been updated in a wide-ranging and sophisticated study of **BI-Wsh** undertaken in 2008, which led to the following updated criteria:

> *"The difference in mean wind velocity **parallel** to the aircraft trajectory may not exceed **7 knots with the speed change taking place over a distance of at least 100 m**"*

> *"The difference in mean wind velocity **perpendicular** to the aircraft trajectory may not exceed **6 knots with the speed change taking place over a distance of at least 100 m**"*

In addition …

> *"The horizontal turbulence level caused by a stand-alone obstacle in combination with the meso-scale surface roughness must remain below an RMS value **4 knots**"*

PART B

Criteria for Triggering Detailed Assessments of the Potential for Building-Induced Windshear to Impact on the Safety of Airport Operations

6 WAKE CHARACTERISTICS BEHIND BUILDINGS

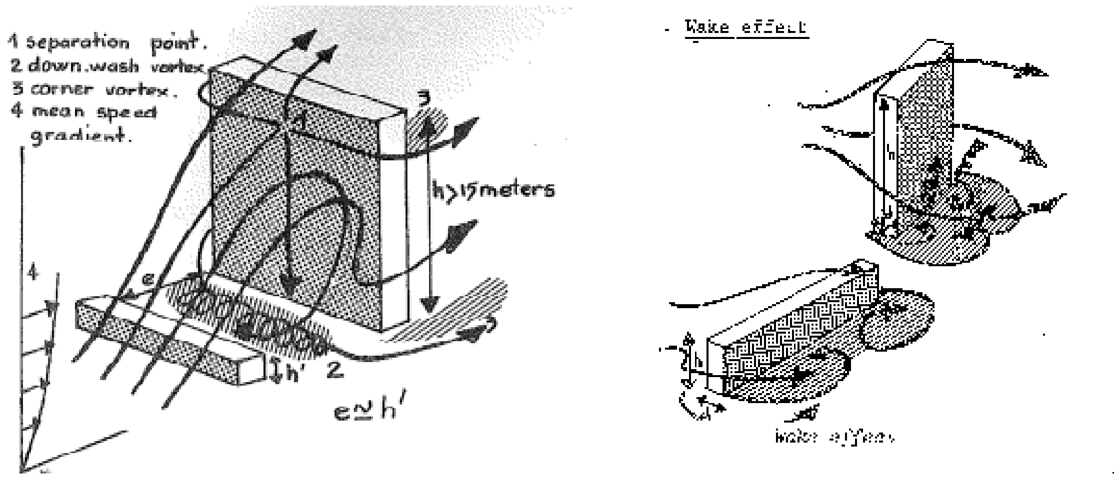
In **Section 2**, the basic pattern of wake flow behind a building ("bluff" body) was introduced. In this section, the extent of windflow disturbance in the wake region will be further explored using previous studies of simple building shapes.

6.1 General Windflow Characteristics Around Buildings

Ref: Gandemer (1975),
"Wind Environment Around Buildings: Aerodynamic Concepts"

Gandemer established a standard terminology for many of the basic windflow mechanisms around buildings, including the downwash which occurs as the wind strikes the windward façade of a building as well as other important flow mechanisms in the building wake region – refer **Figure 23** examples.

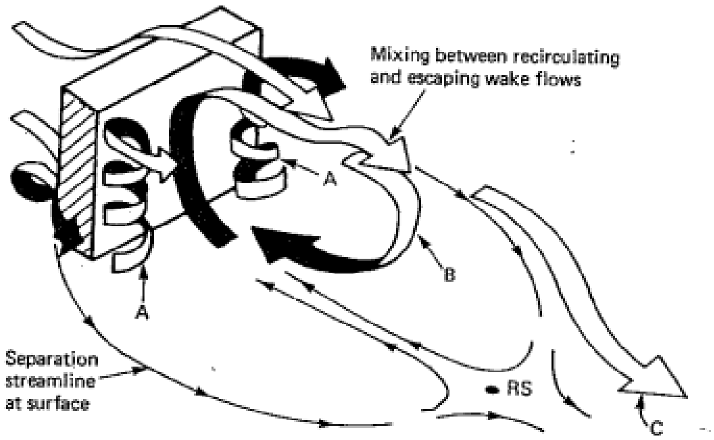
Figure 23 Sample Windflow Mechanism Diagrams from Gandemer (1975)



Ref: Cook (1989),
"The Designer's Guide to Wind Loading of Building Structures – Part 1"

The area of specific interest to this study is the wake region behind a "bluff" body like a building. A conceptual diagram of the wake region is shown in **Figure 24**.

Figure 24 Wake Circulation Behind Slab Block (RS = Rear Stagnation Point)



In **Section 2**, the windflow around a building was split into three flow regions: (a) the approaching and downstream flow which moves past and around the building in more-or-less an undisturbed manner (in terms of wind speed magnitude and turbulence level), (b) the cavity or re-circulating region immediately behind the building, and (c) the thin shear layer zones which mark the transition between regions (a) and (b).

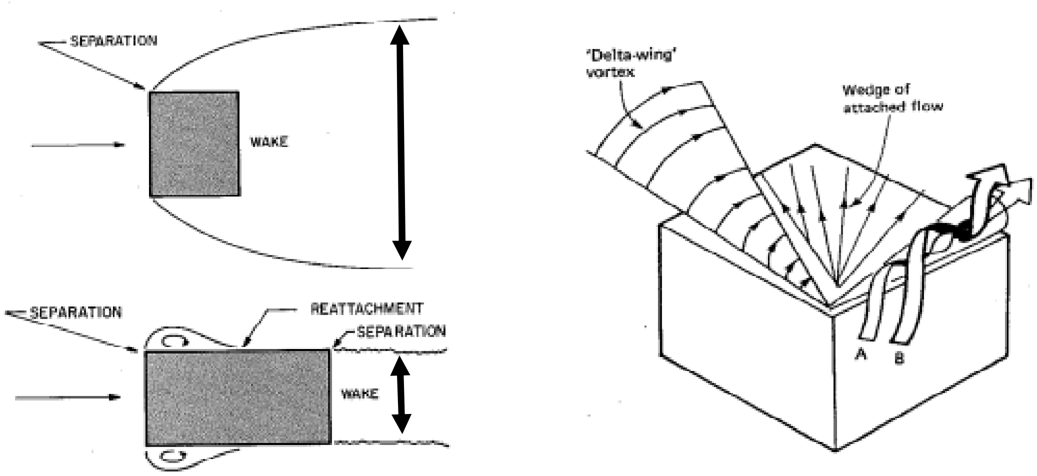
While the above description is essentially correct and adequate for most *wind engineering* applications, in the present instance, further consideration needs to be given to the region of disturbed wake flow behind the building. In fact, the wake behind a building can be divided further into two parts – a near-wake and far-wake.

- The **near-wake** is the cavity region of re-circulating flow (containing re-circulating eddies) immediately behind the building. This region is bounded by the ground surface below, the building upstream and free streamlines (shear layer zones) which extend from the top and sides of the building to a re-attachment "RS" (rear stagnation) point downstream. Studies have shown that, for a wide range of building shapes, the re-attachment point lies up to 5 building heights downstream of the building.
- It is important to appreciate that the wake does not restore itself completely to its upwind (undisturbed) condition immediately downstream of "RS". In fact, there is a region, termed the **far-wake**, which trails further downstream before it eventually blends with, and hence cannot be distinguished from, the surrounding flow. This takes quite a few more building heights distance-wise to occur.
- The principal flows within these two wake regions are marked by arrows. Looking down from above the building, there is a horseshoe vortex which surrounds the building at ground level; "A" is a pair of vertical vortices driven by the flow from the horseshoe vortex which surrounds the building; "B" is a circulation which penetrates through the shear layer zone above the building height, dragging airflow from the "A" vortices; "C" indicates airflow able to escape the near-wake flow region.

The above general description will vary depending upon building shape, building aspect ratio (ie height to width/depth ratio) and building orientation to the oncoming flow. Two building characteristics which have a marked influence on wake flows are shown in **Figure 25**.

- The width of a wake behind a building will be influenced by whether the initial flow separation is able to "re-attach" itself to the building; this is possible if the building is relatively long in the direction of the flow. Broad buildings (ie facing the wind) with shallow depth (ie in the direction of the wind) have larger relative wake widths than buildings with the opposite characteristics.
- Rectangular buildings with an oblique orientation to the wind (refer diagram on the right) tend to form very strong "delta-wing" vortices at their leading corner which can persist in the downstream flow for considerable distances (this is discussed in subsequent sections).

Figure 25 Some Wake Flow Characteristics of Interest: Re-Attachment and Delta-Wing Vortices



6.2 Wake Flow Behind a Solid Barrier

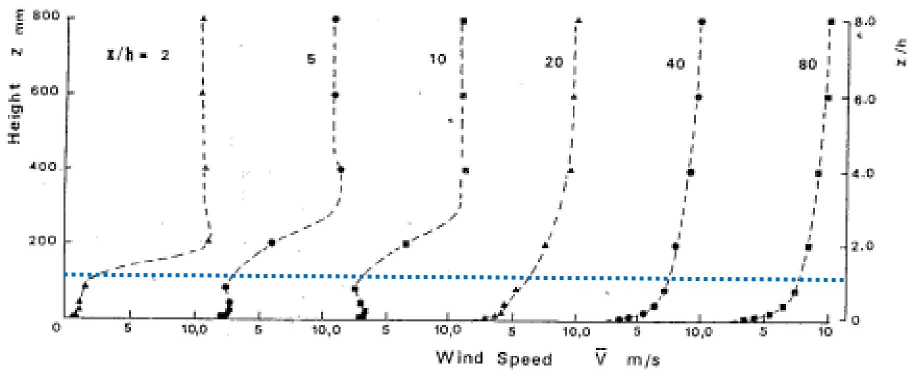
Ref: Holmes & Osonphasop (1983),
"Flow Behind Two-Dimensional Barriers on a Roughened Ground Plane, and Applications for Atmospheric Boundary-Layer Modelling"

In the Holmes and Osonphasop (1983) study, the mean wind profiles downwind of three solid barriers (100 mm, 200 mm and 400 mm in model scale height, shown as blue lines) were studied via wind tunnel testing at a model scale of 1:200 (ie the barriers corresponded to full scale heights of 10 m, 20 m and 40 m). The resulting downstream mean wind profiles are shown in **Figure 26**.

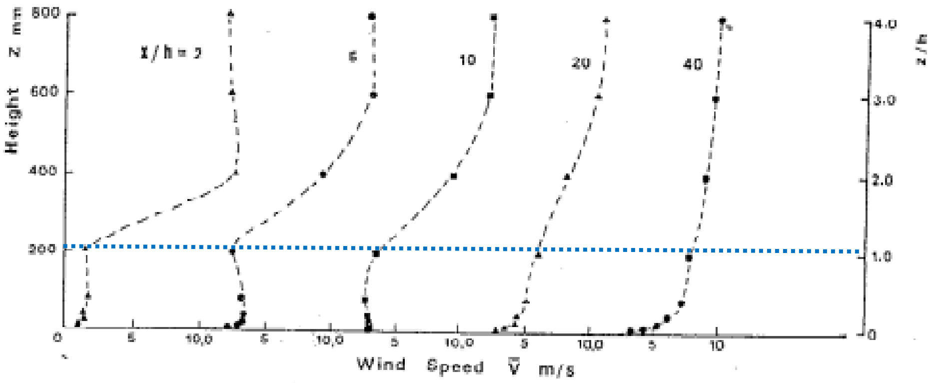
The drop in mean wind speed behind the barrier (or velocity deficit) can be seen to extend to well past 10 building heights (x/h=10) downstream. Also of interest is the vertical extent of the disturbance of the wind profiles, which appears to be above twice the height of each barrier.

Figure 26 Mean Wind Speed Profiles Downstream of Three Solid Barriers

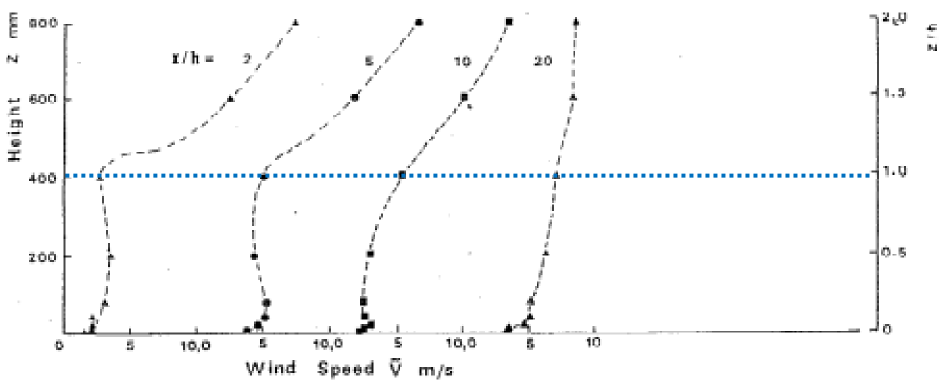
100 mm Barrier



200 mm Barrier



400 mm Barrier



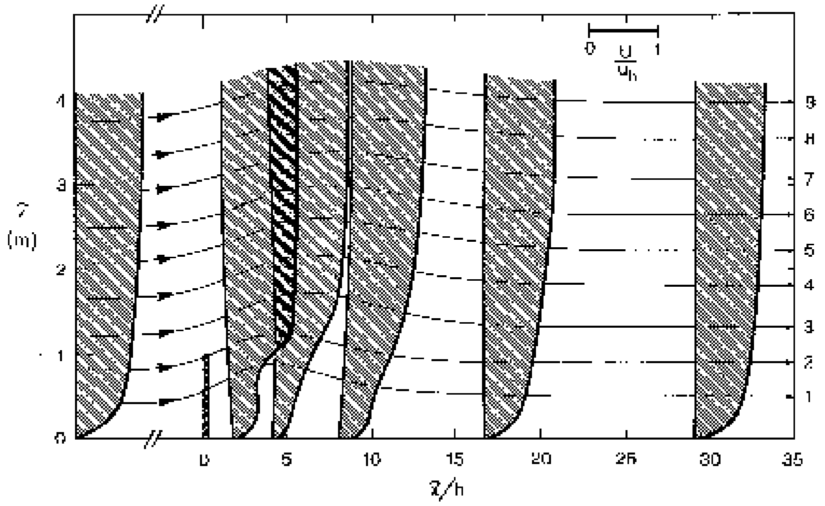
6.3 Wake Flow Behind a Porous Barrier

Ref: Bradley & Mulhearn (1983),
"Development of Velocity and Shear Stress Distributions in the Wake of a Porous Shelter Fence"

Ref: Finnigan & Bradley (1983),
"The Turbulent Kinetic Energy Budget Behind a Porous Barrier: An Analysis in Streamline Co-ordinates"

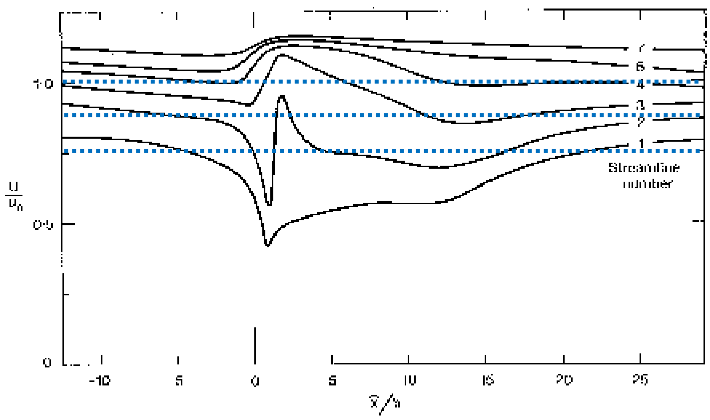
In these studies, full-scale measurements were made of the wake behind a barrier of 50% porosity under neutral stability atmospheric conditions (ie essentially horizontal windflow). Samples of the wind data recorded in these studies are shown in **Figure 27** showing the progression of velocity profile from an upwind (unaffected) state to various downstream locations behind the barrier. The impact of the barrier on the wind profile is immediately apparent and pronounced until a downstream distance of between 5 to 10 times the barrier height. At distances greater than 15 times the barrier height, the velocity profile appears to have been restored to its upwind (undisturbed) form.

Figure 27 Velocity Profiles at Various Distances Downstream of the 50% Porous Barrier



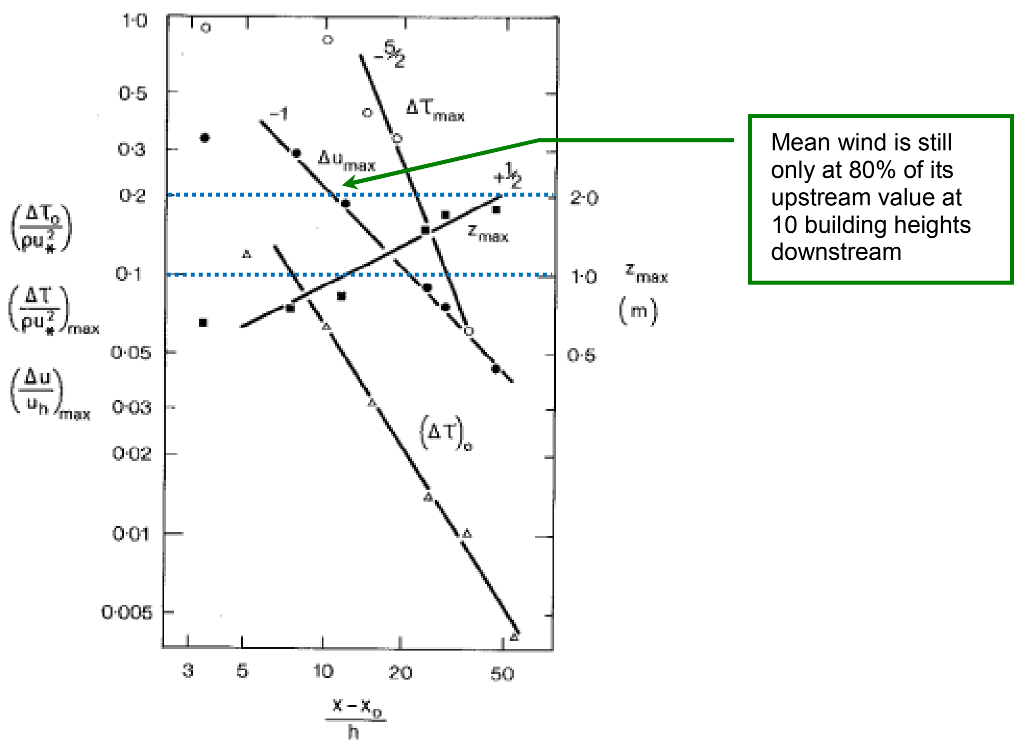
In **Figure 27**, a series of vertically spaced streamlines are numbered "1" to "9". The variation of the ratio of local velocity compared to the upstream velocity at the height of the barrier, u_h, is shown in **Figure 28**. The divergence of each streamline is apparent to more than 10 times the barrier height downstream, with streamlines "4" and above seeing modest increases in magnitude and the lower streamlines seeing significant decreases in magnitude. Once again, it is noted that these flow disturbances are for a "porous" barrier, not a "solid" barrier.

Figure 28 Variation of Velocity Deficit Ratio Along Representative Streamlines



Turbulence levels as well as mean winds were examined in these studies. Key flow parameters are summarised in **Figure 29** showing the downstream changes as a function of building height ratio. The mean speed for example is restored to around 80% of its upwind (unaffected) magnitude at a distance of around 10 times the barrier height and 90% at 20 times the barrier height. Importantly, it can be seen that the wake-induced changes in the flow parameters selected (eg mean speed, U, shear stress, τ, etc) do not diminish at the same rate.

Figure 29 Changes in Key Flow Parameters Downstream of a 50% Porous Barrier



6.4 Wake Flow Behind Square and Rectangular Buildings

Ref: Peterka & Cermak (1983), "Turbulence in Building Wakes"

In this landmark study, the mean velocity and turbulence characteristics of building wakes were measured via model scale testing in a boundary layer wind tunnel. The study investigated the mean velocity deficit and the increase in turbulence (or turbulence "excess") relative to the undisturbed flow upstream.

- Eight buildings were tested, of either square or rectangular cross-section and with aspect ratios ranging from less than 1:1 (ie building height less than the building width) to 4:1.
- The upstream wind profile used in the testing corresponded to a suburban type terrain, typical of terrain conditions around many larger urban airports.

Interestingly, the introduction in this paper cited the need to quantify the potential impact of building development in close proximity to airports (especially inner urban airports) as one of the reasons for carrying out the study.

The study recognised a number of highly relevant characteristics of building-induced wake flows:

- Firstly, it was recognised that the extent of the wake and flow behaviour within the wake were highly dependent on the overall dimensions of the building (width to depth ratios and width to height ratios) and shape details (eg rounded corners, projections, etc) as well as upstream flow conditions (open country terrain flow, suburban terrain flow, etc).
- Secondly, the study recognised that the wake was not a simple region which accounted for all building-induced flow impacts. Rather, the extent of the wake had to be defined in terms of the particular parameter of interest. Thus, some flow characteristics, eg the discrete vortices created by the wake were seen to persist in the flow at distances well beyond the point where other flow parameters such as the mean wind speed had essentially been restored to their upwind (undisturbed) value.

An informative example of the results is shown in **Figure 30** and **Figure 31** for a building with model scale dimensions of width 16 cm, depth 5 cm and height 6.5 cm – the “width” is the dimension of the building perpendicular to the oncoming flow direction.

Figure 30 shows the changes to mean wind speed at different building height distances (X/H) downstream of the building. The immediate impact of the building can be seen in the first profile at half a building height distance from the building (X/H=0.5). At the height of the building, the velocity defect is around 40%. The impact of the building can be seen to extend well past 10 building heights downstream. Of particular interest is the vertical extent of the mean flow disturbance which increases from 1.5 times the building height close to the building itself to over 3 times the building height further downstream.

Figure 30 Vertical Profiles of Velocity Defect Behind Rectangular Building (W=16,D=5,Ht=6.5)

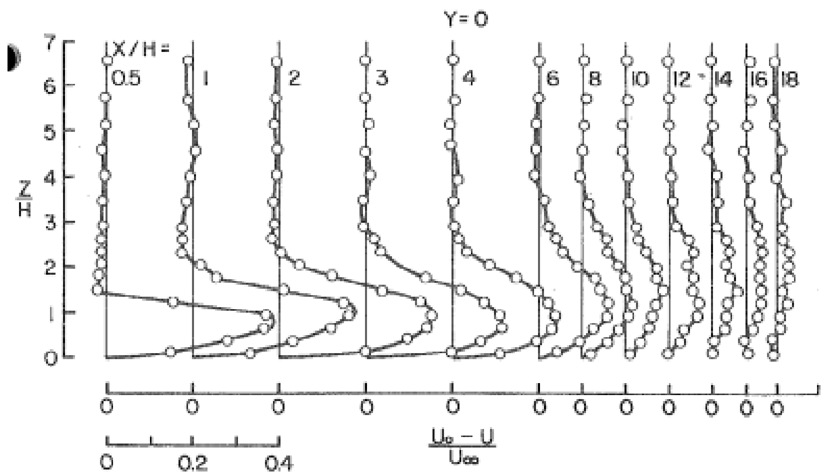


Figure 31 shows the corresponding changes to the turbulence behind the same building, expressed in terms of the change in turbulence intensity (the “intensity” of turbulence is the ratio of turbulence to mean wind speed). Since the level of turbulence increases in the wake, it is usually termed the turbulence “excess”.

The increase in turbulence intensity behind the building is close to 50%.

It can be seen that the vertical extent of the disturbance to turbulence increases quickly from 2 times the building height close to the building itself to over 4 times the building height further downstream. Importantly, these results suggested that the extent of disturbance to turbulence did not match the extent of disturbance to mean wind speed.

Figure 31 Vertical Profiles of Turbulence Excess Behind Rectangular Building (W=16,D=5,Ht=6.5)

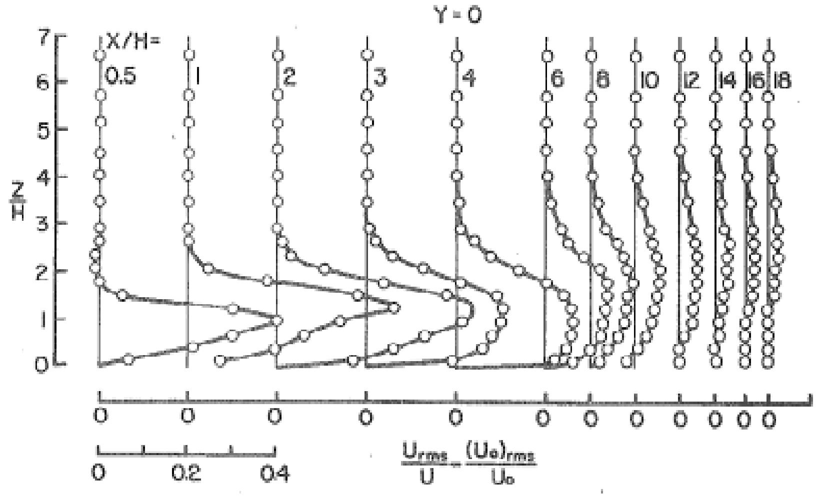
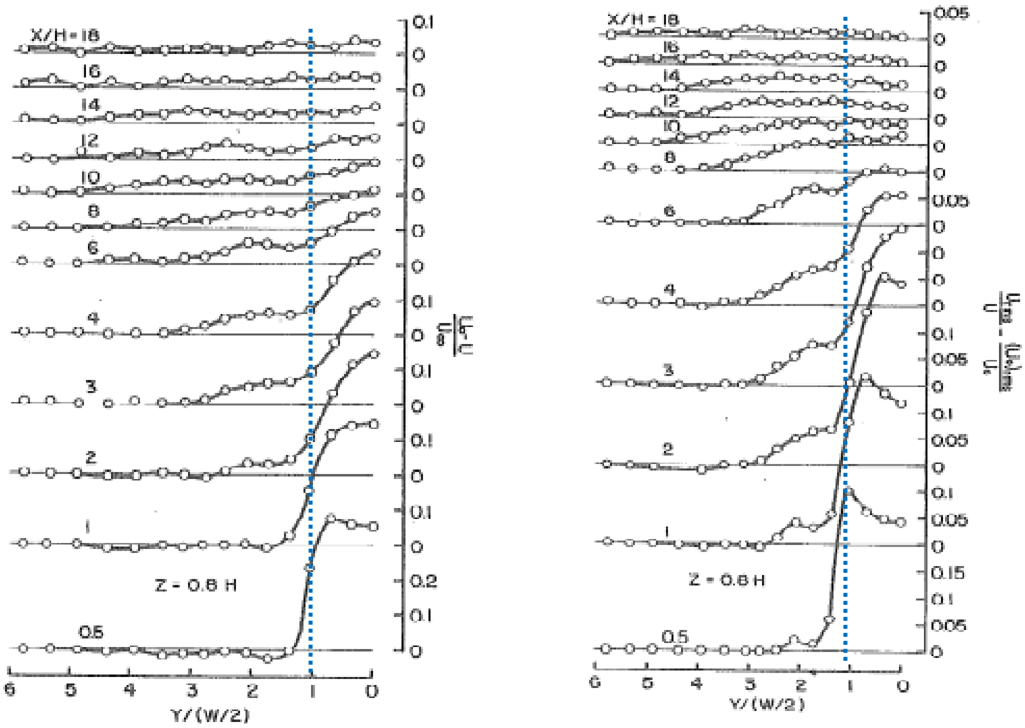


Figure 32 shows the corresponding horizontal profiles of mean velocity and turbulence intensity at a height of 80% of the building height. These diagrams provide an excellent view of the lateral extent of the wake behind the rectangular building (at this height). Wake separation begins close to the edge of the building (Y/H/2=1) and spreads out to over two building widths further downstream.

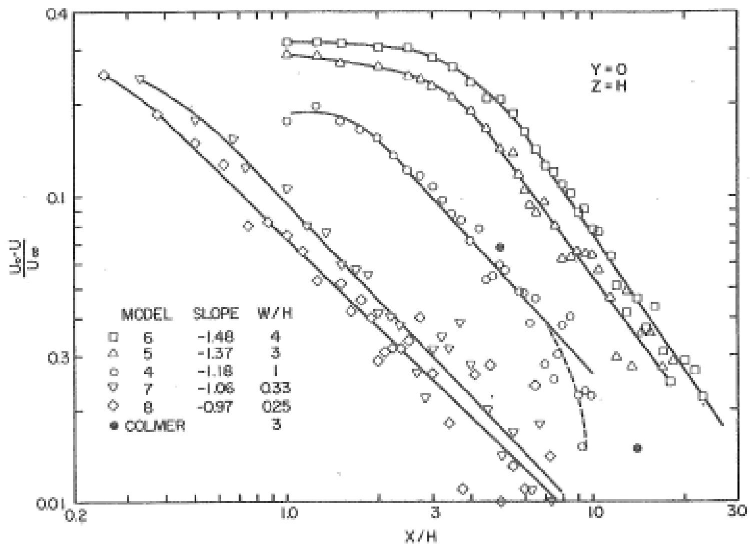
Figure 32 Horizontal Profiles of Velocity Defect and Turbulence Excess Behind Rectangular Building (W=16,D=5,Ht=6.5)



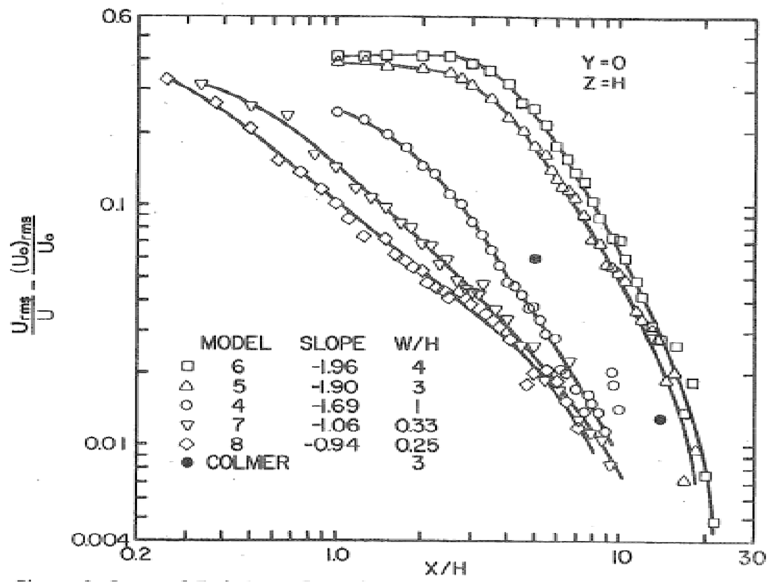
The results for five test buildings with different W/H ratios are summarised in **Figure 33**, showing the mean velocity deficit and turbulence intensity excess at the top height of the buildings. The distance it takes for the mean wind speed to return to its upstream value varies from 1 times the building height (building “8”) to almost 10 times the building height (building “6”).

Figure 33 Selected Summary of Peterka and Cermak (1983) Test Results

Mean Velocity Deficit



Turbulence Excess

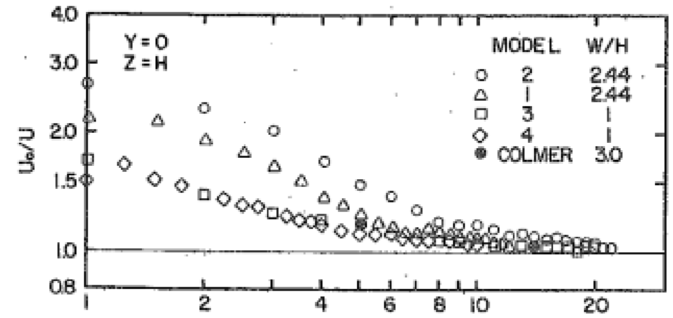


An alternative representation of building wake characteristics is presented in **Figure 34**, which shows the straight ratios of mean wind and turbulence intensity (as opposed to their relative ratios) plotted along a normalised X/H axis. Buildings “3” and “4” are cubical buildings whose dimensions vary by a factor of two; Buildings “1” and “2” are rectangular buildings whose dimensions also vary by a factor of two. The Building “3” and “4” mean wind speed results are almost identical, but not their turbulence results. The Building “1” and “2” results for mean wind and turbulence both differ. In the latter case, the wake impacts are more pronounced for the larger of the two buildings. Finally, it can be seen that the wake impacts differ by a factor of two or more depending upon building shape and height.

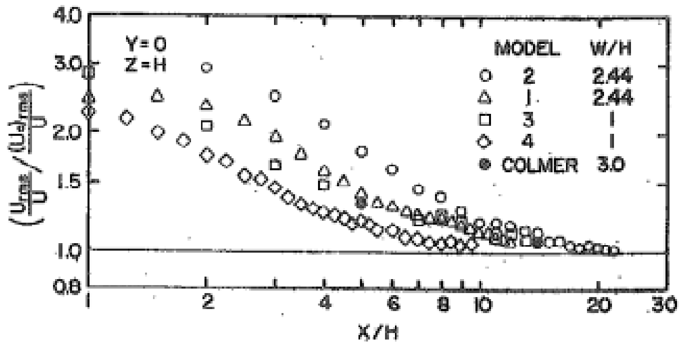
These results suggest that **different normalising factors** would be required to develop a model describing all wake effects (ie the changes to the mean speeds as well as the turbulence) for buildings of different cross-section (square, rectangular, etc), different aspect ratio and actual size.

Figure 34 Selected Summary of Peterka and Cermak (1983) Test Results (Ratio Results)

Mean Velocity Ratio
(Uo – undisturbed velocity)

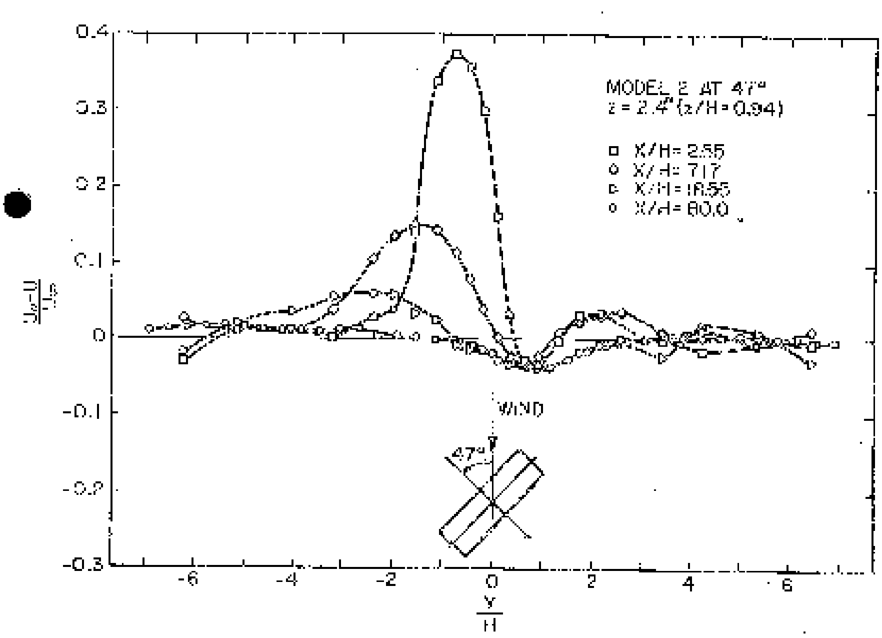


Turbulence Intensity Ratio



One final result of significance is shown in **Figure 35**, where test building “2” shown in **Figure 30** to **Figure 32** was rotated relative to the oncoming wind direction to an angle of 47º. The (predictable) asymmetric nature of the wake is evident in the displacement of the area of maximum disturbance away from the centreline. What is somewhat surprising however is the extent of the wake. All of the previous results suggest that significant wake anomalies tend not to be seen more than 15 to 20 building heights downwind. The building “2” 47º results show wake impacts well beyond this distance downstream. Of particular interest is the mean velocity variance in the region Y/H=0.5-1.0, which persists to 80 building heights downstream. Peterka and Cermak suggested that this feature was evidence of a vortex pair which decayed very slowly and which was probably created by the leading edge vortices at the leading roof corner – refer **Figure 19**.

Figure 35 Horizontal Profiles of Mean Velocity Deficit for Building “2” at 47º

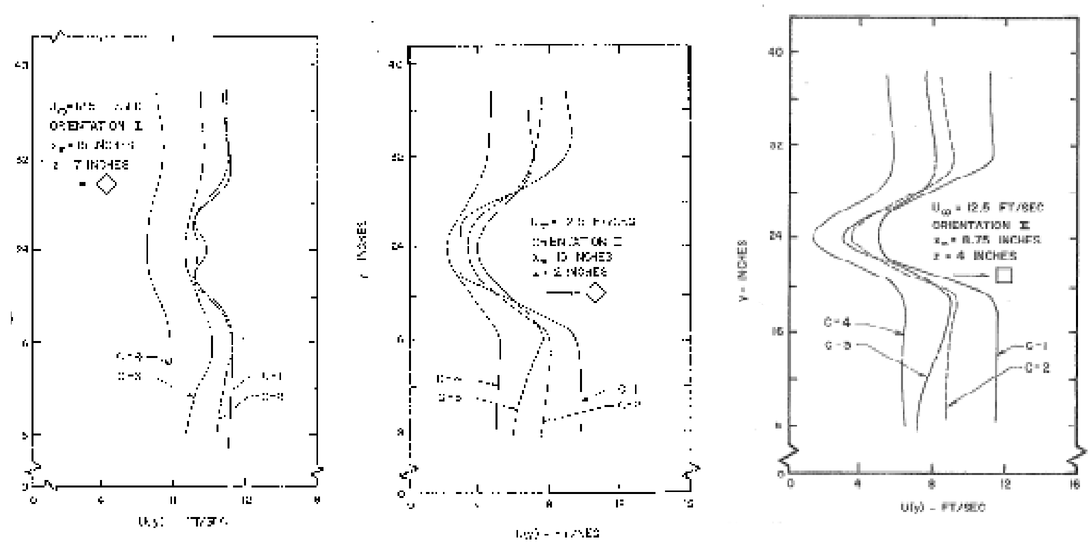


Ref: Corke, Nagib & Tan-atichat (1983), "Flow Near a Model of a Building in Simulated Atmospheric Surface Layers Generated by a Counter-Jet Technique"

This study examined the influence of the upstream boundary layer profile on the resulting wake flow behind a square building of aspect ratio 2:1 (building height twice the building width). Two wind directions were examined – wind at 45º to a face (Orientation I) normal to a face (Orientation II). Four upstream terrain profiles C1-C4 were examined, ranging from an open country (flat) terrain to an urban terrain (medium sized buildings in the immediate surrounds). **Figure 36** shows the variation of horizontal wake flow at several representative heights:

- There is a very significant difference in the relative disturbances of both the mean velocity deficit (top three diagrams) and turbulence excess (bottom three diagrams) for the four different terrain profiles.
- The greatest relative changes, ie largest wake effects, occur for **open country terrain**, where mean winds (at the same height) are higher and turbulence levels are lower in the upstream flow.

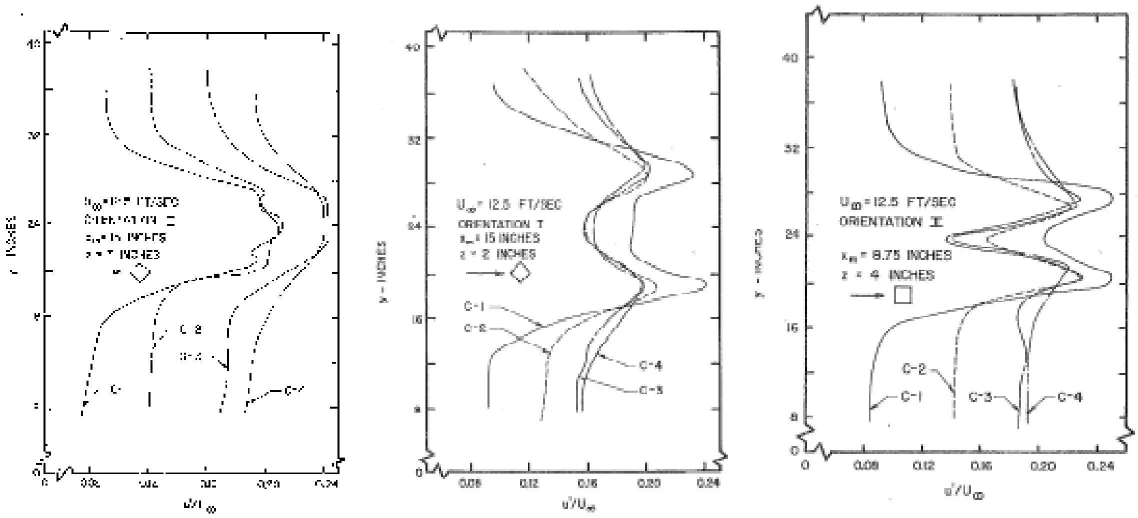
Figure 36 Influence of Upstream Terrain Profile on Wake Flow



(a) 45º flow, X/H=2, Z=~H

(b) 45º flow, X/H=2, Z=~1/4H

(c) 0º flow, X/H=1, Z=~1/2H.



6.5 Universal Representation of Recirculation Length

Ref: Fackrell (1983),
"Parameters Characterising Dispersion in the Near Wake of Buildings"

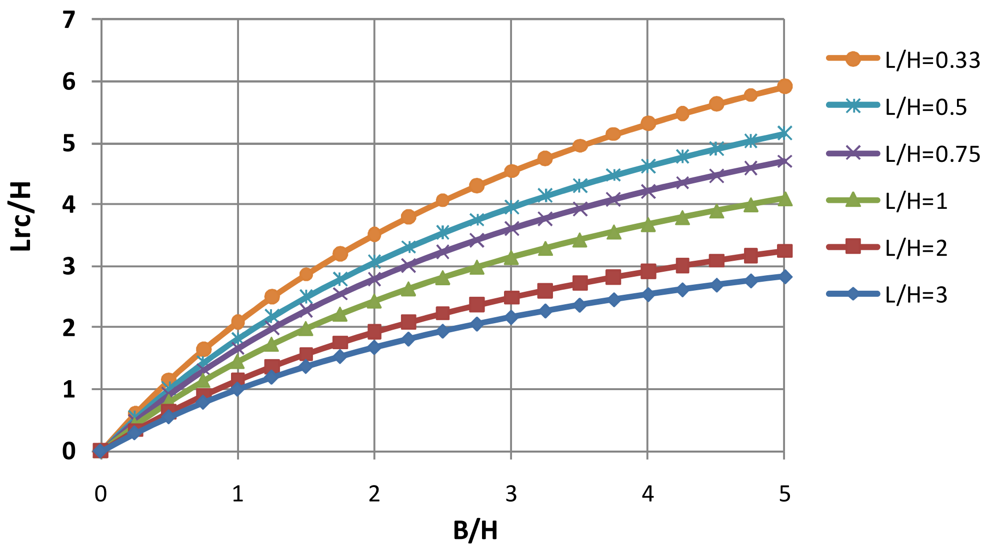
This study examined the wake parameters of interest in relation to pollutant concentrations in the wake flow of buildings, including the distance from the rear of the building to the point of re-attachment of the separation shear layers, ie the recirculation region length, and the pollutant "residence" time (ie the time for the concentration of an aerosol in the near wake to decay to 1/*e* of its source value. A large number of rectangular building shapes, all with sharp corners, were examined covering a wide range of B/H ratios from 0.33 to 5 (B = width of the building perpendicular to the wind, H = building height) and L/H ratios from 0.05 to 6 (L = length of the building in the direction of the windflow). Tests were also done with different turbulence intensities, ranging from a reasonably "open" terrain to a relatively dense "suburban" terrain. The range of different B:L:H ratios allowed the tests to distinguish the cases when re-attachment of the flow on the building itself occurred, thereby influencing the extent of the wake behind (refer **Figure 25**).

The test results were used to develop the following relationship defining the recirculation region length, Lrc, as follows:

$$Lrc / H = 1.8 (B/H) . [(L/H)^{0.3} . (1.0+0.24 (B/H))]^{-1}$$

The above relationship is plotted in **Figure 37**. Lrc was given two limiting range values, namely, values of Lrc for ratios of L/H less than 0.33 were taken to be those at L/H=0.33 and values of Lrc for ratios of L/H greater than 3 were taken to be those at L/H=3. The match between Fackrell's recirculation length relationship and his wind tunnel test measurements (as well as those of others examined in his study) was better than ±20% for all tests cases.

Figure 37 Universal Algorithm for Calculating Recirculation Length, Lrc



Some limited tests were carried out for selected building shapes (eg cubes) with an oblique, 45º approach flow, which gave slightly larger values of Lrc to those indicated in **Figure 37**. Several tests were also done on hemispherical shaped (dome) roofs resulting in smaller values of Lrc.

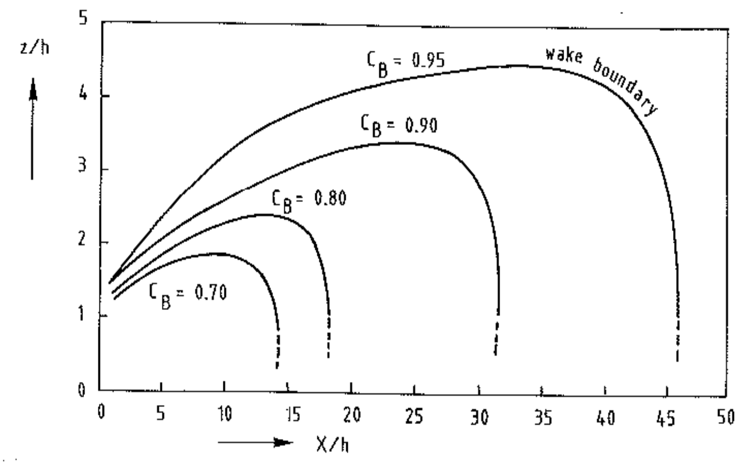
6.6 Building Wake Velocity Deficit Estimation

Ref: Leene (1992),
"Building Wake Effects in Complex Situations"

This paper drew upon the results documented in a TNO study entitled, "**Handbook on Obstacle Wake Effects Related to Wind Turbine Siting**" to examine the impact of new building developments on the local pedestrian wind climate. It offers a series of simple algorithms predicting the impact of a building wake on mean velocities of relevance to the present study and is broadly consistent with the results of the others studies included in this section.

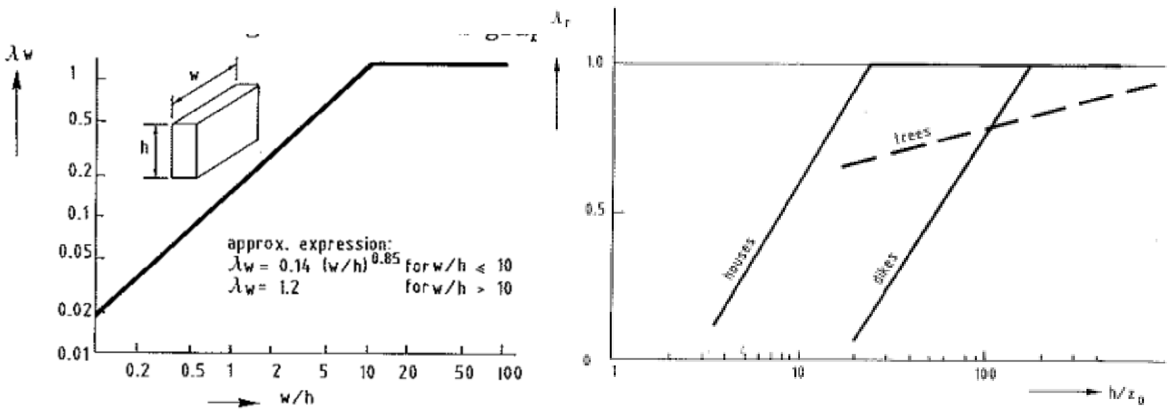
The start point is a series of iso-velocity contours – refer **Figure 38** – giving a dimensionless ratio, C_B, equal to the value of the local velocity compared to its upstream (unaffected) value. The C_B ratios are given as a function of X/H (X = distance downstream from building rear face) and Z/H (Z = height above ground). The C_B ratios are for a reference building with W/H=8 (W = width of the building facing the wind). For the chosen reference building, it can be seen that the mean wind speed recovers to around 80% of its upstream value at around 18 building heights downstream and the disruption to the flow for this contour (C_B=0.8) extends to over twice the height of the building.

Figure 38 Leene (1992) Iso-Velocity Contours for the Reference Building (W/H=8)



A series of adjustment factors are then provided to account for (a) different W/H ratios, (b) different upstream terrain roughness, (c) varying angle of attack of the wind, and (d) "end" effects. Two of these factors are shown in **Figure 39** for the W/H and terrain roughness adjustment factors. It can be seen for example that the wake disturbance dimensions reduce to around 0.3 of their reference values for a building with W/H=2.

Figure 39 Leene (1992) Iso-Velocity Adjustment Factors for W/H and Terrain Roughness



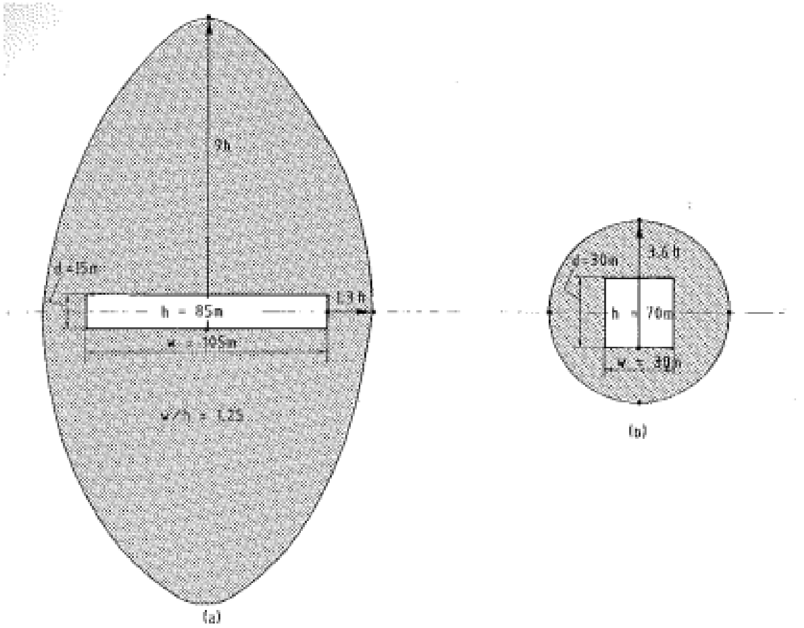
It is of interest to evaluate the wake disturbance lengths for a representative set of W/H values in typical open type terrain. These are shown in **Table 3**. The results are shown as functions of building height, H, and are for buildings whose length in line with the windflow is such that reattachment does not take place.

Table 3 Distance Downstream for Various Mean Velocity Deficits (H=building height)

Mean Velocity Deficit Recovery	**W/H Ratios = 1**	**2**	**4**	**6**	**8**
60%	1.8 H	3.5 H	7 H	10 H	13 H
70%	2.2 H	4 H	8.5 H	12 H	15 H
80%	3 H	5 H	10.5 H	14 H	18 H
90%	5 H	9 H	17 H	25 H	32 H

Sample diagrams of the influence area of two buildings of about the same height but different W/H ratio are shown in **Figure 40** indicating the extent of the CB 95% contour at ground level, ie outside of this area, mean wind speeds are at least 95% of their upstream (unaffected) value.

Figure 40 Wake Influence Area (CB=95%) of Two Rectangular Buildings (W/H=1.25, W/H=0.43)



One final result of interest presented by Leene was a survey of pedestrian comfort wind tunnel test results undertaken at TNO during the period 1984-1987. The survey covered 19 buildings of height varying from 40 m to 157 m and compared the maximum wind speed experienced at ground level behind the building and the approach wind velocity at roof level of the building. It found the following:

- The maximum mean wind speed close to the ground in the windfield surrounding the wake behind the building is roughly equal to the mean wind at the top height of the building in the approach flow.

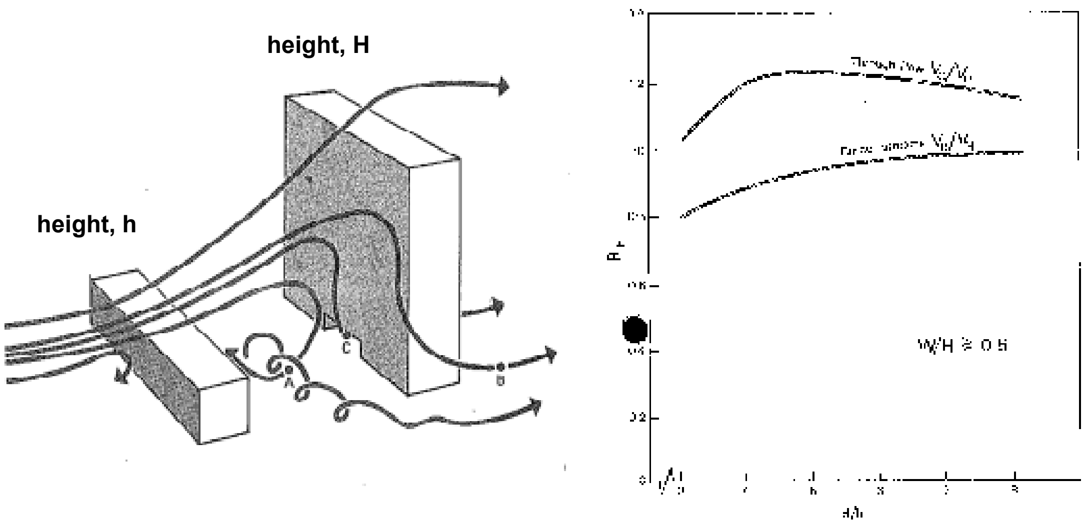
The significance of the above is further explored in **Section 6.7**.

6.7 The Influence of Height on Building Wake Mean Velocity Deficit

**Ref: Lawson & Penwarden (19XX),
"The Effects of Wind on People in the Vicinity of Buildings"**

This study was particularly focussed on pedestrian level winds and the influence of buildings in producing elevated wind conditions at ground level through mechanisms such as downwash, etc. One particular set of experiments undertaken in this study looked at the impact of two buildings in line with the main windflow and the resulting ratio of the highest level of mean wind speed at ground level in the immediate downstream wake area, V_B, compared to the mean wind speed in the approach flow at building height, V_H. These test results are shown in **Figure 41**.

Figure 41 Ground Level Wind Speeds in a Building Wake with an Upstream Building Present



Of particular interest is what occurs to the ratio V_B/V_H as H/h becomes very large (ie effectively eliminating the impact of the upstream building). In this instance, it appears that V_B (the highest ground level mean wind speed caused by the building) approaches the same magnitude as V_H.

In other words, the flow mechanisms present in a building wake (corner vortices, etc) result in a momentum exchange between the wind at upper levels (ie at the top of the building) in the approach flow and the wind at ground level downstream of the building. This feature has been observed in numerous other wind tunnel studies – refer for example the compilation of TNO wind tunnel test results discussed in the previous section - and leads to the following important outcome:

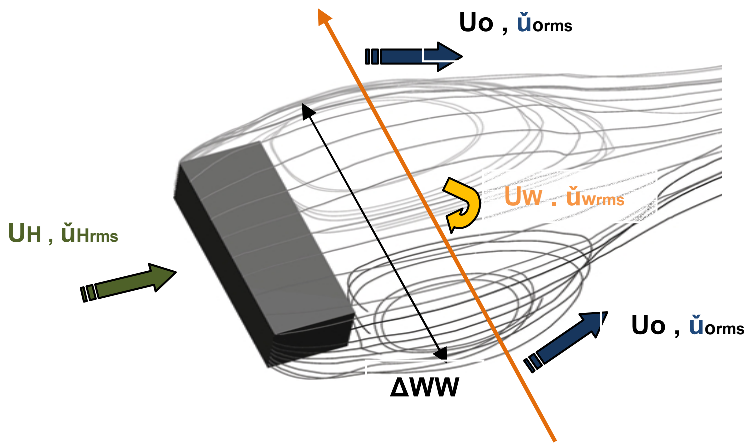
- The **maximum resulting ground level mean wind speed** downstream of a building (and just outside of the wake cavity region) will be of the **same order** as the **mean wind speed at the top of the building in the approach flow - regardless of building height**.
- As mean winds generally increase in height above ground level (refer **Figure 3**), it follows that **taller buildings** will generate **higher maximum mean winds at ground level in their wake region**.
- Further downstream, ground level mean winds (just outside of the wake) will decrease as they gradually approach their upstream unaffected value (at the same height).
- If one then considers an object traversing across the wake behind a building perpendicular to the wind (refer **Figure 7**), it is clear that, close to the ground, the **mean wind speed variance** experienced by the object from one side of the wake cavity region to the other will **increase** as the **building height increases**.

6.8 The Magnitude of Building-Induced Windshear Mean Wind Variance

To identify key parameters of interest to the present study, the following definitions are developed as depicted in **Figure 42** where "U" denotes the mean wind speed and "ǔ" denotes the turbulence level (note that Uo and ǔorms are assumed to be close to the ground):

Mean Wind Speed (anywhere in the flow):	**U**
Turbulence Level (anywhere in the flow):	**ǔ**
Building-Induced Wake **M**ean Wind **D**eficit:	**BMD = Uo - Uw**
Building-Induced Wake **T**urbulence **E**xcess:	**BTE = ǔwrms - ǔorms**
Building-Induced **W**ake **W**idth:	**ΔWW**

Figure 42 Building-Induced Wake Parameters of Interest (Building Height = H)



On the basis of the studies discussed in this section, the following general observations can be made as to factors which contribute to the magnitude of **BMD**, **BTE** and **ΔWW**

- The maximum magnitude of **Uo** (close to the ground) will be **approximately the same** as the magnitude of **UH** (approach flow mean speed at height, H), **regardless** of the actual building height.
- The mean wind within the re-circulating wake region, **Uw**, will be low (in magnitude) and will vary between being towards and away from the building. Hence, **Uw** will have an average vector magnitude **close to zero**, regardless of the actual building height or any other building dimension parameters. For some building geometries, the average **Uw** vector at some locations in the wake cavity region may in fact be towards the building, ie in the opposite direction to **Uo**.
- Given the above, a reasonable estimate for the maximum magnitude of **BMD**, the mean wind speed variance experienced by an object traversing across the building wake, is simply **UH**
- **BMD** will **increase** if the building height, H, **increases**. This will apply at any point downstream of the building.
- All other parameters being equal, both **BMD** and **BTE** will **increase** if the terrain conditions upstream of the building are reasonably "flat" and more "open" (ie free of obstacles).
- The width of the wake, **ΔWW**, will increase with building width (ie the building dimension perpendicular to the oncoming windflow). **ΔWW**, will be **larger** if the building width perpendicular to the oncoming windflow is greater than the building depth in line with the oncoming windflow, In this instance, **ΔWW** will be of the order of twice the building width.

The preceding observations of the magnitude of **BMD** and rate of recovery of the mean velocity deficit described in previous sections can be combined to produce estimates of **BMD** values as a function of the mean velocity of the approach flow at building height, V_H.

One set of representative values is in **Table 3**. The building is assumed to be 30 m to 40 m in height and rectangular in shape with a length in line with the windflow such that reattachment does not take place, ie the in-line length is less than the building width. The values apply to the case of windflow striking the building perpendicular to the main façade "width" dimension, W, and assume reasonably open flat terrain upstream of the building.

The magnitude of **BMD** (the mean velocity deficit) is given in terms of a ratio of V_H. As an example, for a building of width-to-height ratio W/H = 4, the mean velocity deficit encountered by an object traversing the building's wake at a distance of 10 x building height would be equal to 22% of V_H.

Table 4 Distances Downstream for Various BMD Values (H=building height)

BMD =	W/H Ratios = 1	2	4	6	8
0.48 V_H	1.7 H	3.4 H	6.5 H	9.5 H	12.5 H
0.35 V_H	2.2 H	4.2 H	8 H	11.5 H	15 H
0.22 V_H	3 H	5.5 H	10 H	14 H	18 H
0.11 V_H	5 H	9 H	17 H	24.5 H	32 H

The building height values provided in the **Table 3** (and its accompanying graph) would be:

- greater for wind approaching at an oblique angle
- lower for an upstream terrain of greater surface roughness

Example Calculation:

Building Dimensions:	Width, W = 120 m	Length, L = 30 m	Height, H = 30 m
	W/H = 4		
Approach Mean Speed:	V_H = 10 m/s	(36 km/hr, 19.4 kt)	
Upstream Terrain:	Open, Flat Terrain		
Approach Flow:	Perpendicular to Width, W, façade of building		

BMD:	= 4.8 m/s	9.5 kt	210 m downstream of the building
	= 3.5 m/s	7 kt	240 m downstream of the building
	= 2.2 m/s	4.5 kt	300 m downstream of the building
	= 1.1 m/s	2 kt	510 m downstream of the building
ΔWW:	= 240 m		

Finally, it is noted that the above terminology employed for **BMD** is what would be experienced as the **mean crosswind-induced deficit** if the “object” traversing a building wake were an aircraft.

In the above example, the mean crosswind-induced deficit experience by an aircraft landing on a runway whose centreline is located about 240 m from the nearest face of a building of dimensions 120 m (width), 30 m (depth) and 30 m (height) would be of the order of 7 kt and would be sustained over a distance of more than 200 m.

To obtain a complete understanding of the above example in terms of likelihood of occurrence, it would then be required use the wind rose for the site to calculate the probability of occurrence of the wind having a magnitude of 10 m/s AND approaching the site from the worst-case wind direction (ie firstly over the building and then onto the runway).

6.9 Section 6 Synopsis

The wake flow behind a bluff body (eg a building) impacts both the mean speeds and the turbulence of the oncoming windflow. It comprises several readily identifiable features, most notably the **cavity region** immediately behind the building where **low speed, re-circulating flow** is apparent.

The cavity or **re-circulation region** typically extends up to **5 times the building height**. Wake effects (especially in relation to turbulence) however extend **well past** the recirculation zone, in some cases (depending upon building orientation) to beyond **20 times the building height**.

The extent of the wake (ie the region of disturbance to the upstream flow) – in terms of its physical dimension and the magnitude of the disturbance contained therein – will depend upon **building shape** (eg square, rectangular, etc), **building orientation** (ie building facades perpendicular to the wind, facades at 45º to the wind, etc), **aspect ratio** (height to building width ratio) and **surrounding terrain conditions** (open country terrain, suburban terrain, etc).

For a wide range of simple building shapes, changes to mean winds can occur up to 20 times the building height downstream, although the velocity deficit is usually **modest beyond 10 times the building height downstream**. For square and rectangular buildings with a wide range of building dimensions and oriented with their facades perpendicular to the windflow, the mean wind behind the building recovers to over 80% of its upstream level at a downstream distance up to 10 times the building height.

The disturbance to turbulence appears to be greater in both downstream extent and vertical extent (height above the building). While the disturbance to mean speeds extends not much more than 2 times the building height, noticeable turbulence changes occur up to **4 times the building height**.

All of the above wake effects (to both mean winds and turbulence levels) vary according to the upstream terrain profile. Relatively smooth windflow approaching a building over flat, open country terrain results in the largest relative changes in the resulting building wake.

A particular case of interest is when certain building shapes (including rectangular buildings) are oriented at an **oblique angle** to the approaching windflow. In this case, a pronounced **delta-like vortex** forms at the leading corner of the building and persists in the flow for a considerable distance downstream. In this instance, turbulence levels can be elevated for distance well beyond the point where the mean wind is restored to its upstream (unaffected) level.

The results from wind tunnel tests of various simple building shapes and aspect ratios suggests that a simple “rule” for determining the magnitude of wake disturbance (for both mean winds and turbulence levels) based just on building height, and accurate for any building shape and any combination of building dimensions, is not apparent. For example, two rectangular buildings with exactly the same ratios of width-depth-height but of different actual scale (eg one twice as big as the other) result in different wake impacts relative to their heights.

The consequence of this latter observation is highly significant. If it was desired to determine the extent of building wake effects using a simple prediction rule based for example on the number of building heights downstream, such a rule would have the potential to end up being **highly conservative** if it was required to cover a reasonable range of building shapes and dimensions.

To avoid such conservatism, it would appear necessary to use **quantitative techniques** (eg wind tunnel testing, Computational Fluid Dynamics CFD, etc) to examine the particular building of interest and establish precisely the extent of significant wake disturbance – these techniques are discussed in detail in subsequent sections.

Sections 4.5 to 4.8 establish some useful benchmark values for building-induced wake effects for rectangular buildings in upstream open terrain conditions and for the case of no flow re-attachment (ie building width perpendicular to the flow greater than building length in line with the flow):

- A reasonable estimate for the **potential maximum magnitude of horizontal windshear** (of the mean wind) experienced by an object moving across a building wake (close to the ground) is the **magnitude of the mean wind speed at top of building height in the approach flow**.
- It follows that the **potential maximum magnitude of horizontal windshear** (of the mean wind) experienced by an object moving across a building wake **increases with building height**.
- The potential magnitude of horizontal windshear (of the mean wind) experienced by an object moving across a building wake will be highest if the terrain conditions upstream of the building are "smooth", ie "open" flat terrain.

Table 3 of **Section 6.8** provides a set of estimates which can be used to determine the magnitude of **mean crosswind deficit** of an object moving across the wake behind a building (once again for the case of a rectangular building, height between 30 m to 40 m, no re-attachment, open country terrain).

The **Table 3** estimates are given as a ratio of upstream mean wind speed, V_H (at building height, H). This then provides a direct link with which to establish the likelihood or frequency of occurrence of wake-induced horizontal windshear events of a given magnitude. This frequency of occurrence can be readily determined by calculating the frequency of occurrence of the mean wind speed at the height of the top of the building of concern, taking into account the surrounding terrain and the optimal directionality which has the potential to produce wakes interacting with airport operations.

7 RELIABLE ASSESSMENT OF BUILDING WAKE EFFECTS

There are three broad options for carrying out a wind assessment during the approval stage of a building project with the aim of investigating key environmental issues of interest such as the extent of the wake behind a building and the magnitude of disturbance to mean wind speeds and turbulence levels in the wake:

- Qualitative ("Desktop", "Expert Opinion")
- Wind Tunnel Testing (Using Scaled Models of the Building and Wind)
- CFD Modelling (3-D Computer Simulation)

7.1 Qualitative (Expert Opinion) Wind Assessments

In many regulatory environments, studies of pedestrian (ground) level winds are mandatory prior to the granting of development approval for building projects, especially when taller structures are involved. Such studies are typically performed to investigate wind conditions throughout public access areas within and surrounding the site of interest and to ensure that a comfortable and safe wind environment is maintained around the building of interest.

Qualitative ("desktop" or "expert opinion") studies of wind effects can be made early on in the design process of a building project while the design is evolving from concept to detailed design stage and the external envelope of the building is being refined (and subject to negotiation with the relevant regulatory bodies).

Qualitative studies are based on the best engineering judgement of the consultant undertaking the assessment. The consultant will rely on lessons learned from having undertaken numerous (possibly even hundreds) of wind assessments, including wind tunnel tests and CFD simulations, as well as studying the results of others' investigations.

In such studies, the consultant typically looks for predictable zones of local wind speed-up such as shown in the diagrams illustrated in **Figure 43**.

- Downwash winds are the winds which impact on the windward face of a building and are then deflected downwards to ground level in a vertical direction
- Accelerating shear layer winds are the winds which experience an acceleration around the building edges and roof as the flow moves downstream past the building

In general, the taller the building, the more pronounced the impact on ground level winds – refer the discussion in **Section 6**. Local building details can also influence winds in the immediate vicinity, eg building undercrofts often result in local, intense acceleration of winds.

The grouping of buildings can also have an impact on resulting pedestrian winds:

- Canyon effect winds result when there are rows of parallel buildings (especially taller ones) where the gaps in between line up with prevailing wind directions
- Venturi effect winds result when windflow is forced to pass between two converging buildings or groups of buildings with a resulting intensification of flow

In a desktop study, the consultant is required to estimate the location of likely adverse wind conditions and their potential magnitude. This can then be compared to International Criteria for pedestrian and occupant safety and comfort taking into account the directional characteristics of the local wind climate. Recommendations then follow to ameliorate any such likely conditions using landscaping, porous windbreaks, awnings, canopies, etc.

Figure 43 Characteristic Windflow Pattern “Hot Spots” Around Regular Shaped Buildings

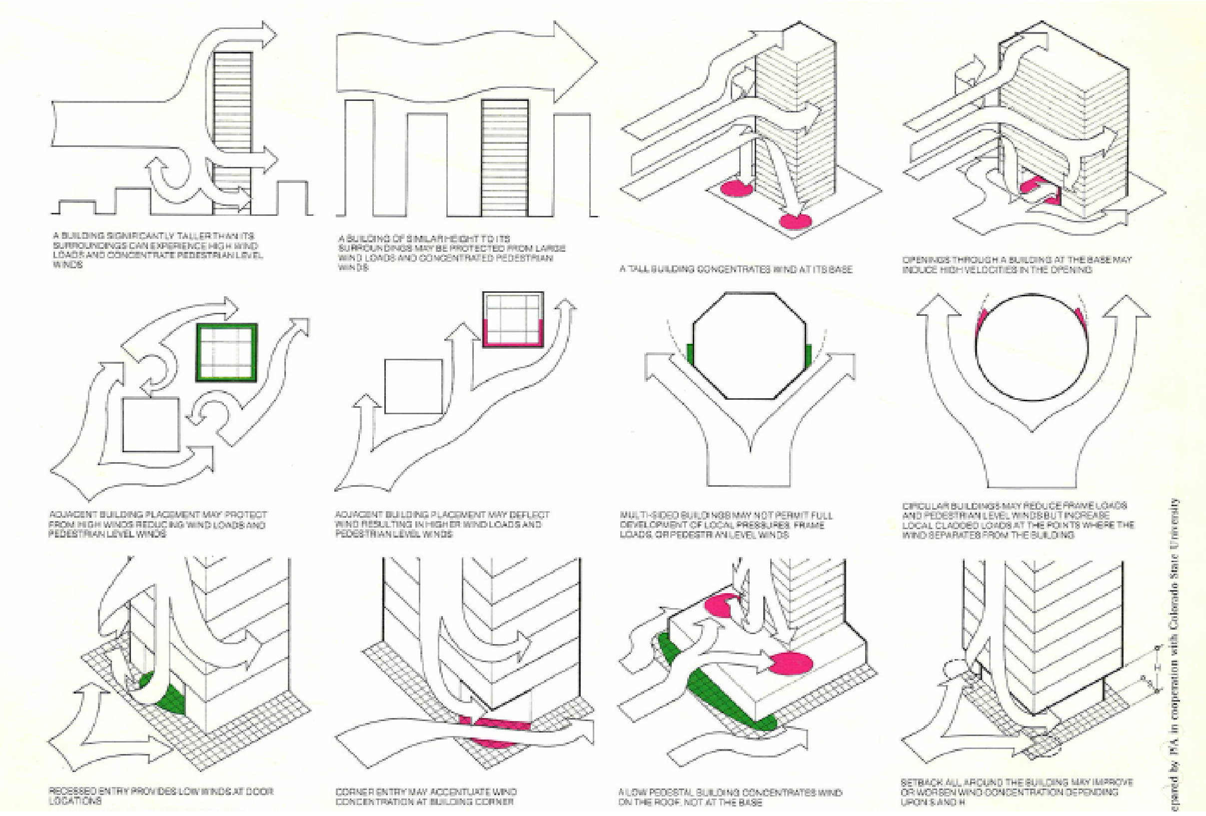


Image Courtesy Colorado State University

The use of qualitative (desktop) studies has been accepted by the proponents of new developments and regulatory authorities alike (especially for smaller building projects) because:

- Such studies can be undertaken with **minimal time** (and hence **cost**)
- **Local** wind speed “**hot spot**” phenomena of interest are usually **reasonably well understood**
- Depending upon the recommendations of the consultant, a detailed follow-up using a more quantitative technique (such as wind tunnel testing or CFD) can always be undertaken during the detailed design phase of the project to refine the assessment and wind mitigation options.

A key aspect of all of the above is that the focus of such studies is invariably limited to ground level wind effects **in the immediate vicinity of the building of concern**, where the **maximal wind disturbance** caused by the building occurs.

The disturbance to the mean wind and turbulence at distances of say 10 or more times the height of the building are almost **never of concern**. Consequently, wind consultants would be unlikely to have an extensive reservoir of past project experience to draw upon in making such determinations, especially for non-regular building shapes.

Accordingly, and in relation to building-induced wake disturbance at the downstream distances of interest to this study (say up to 20 times the building height):

- The outcomes of qualitative assessments of wake effects are likely to vary considerably amongst even “expert” consultants (especially for non-regular building shapes), and hence
- Reliable (and consistent) estimates of the mean wind speed deficit or turbulence excess across the wake are unlikely, especially for non-rectangular building shapes under oblique flow conditions (let alone situations involving multiple buildings).

7.2 Wind Tunnel Testing

Wind tunnel testing of buildings, towers, bridges, etc, has evolved over many decades into a highly sophisticated branch of engineering science. Numerous studies involving full-scale measurements taken on some of the world's tallest buildings and longest bridges have validated the results obtained from model scale wind tunnel testing. Nowadays, the design of any structure of significance will usually involve comprehensive wind tunnel testing to investigate ground level wind conditions surrounding the site and wind loading effects (façade cladding pressures, structural loads, building deflections, building accelerations, etc).

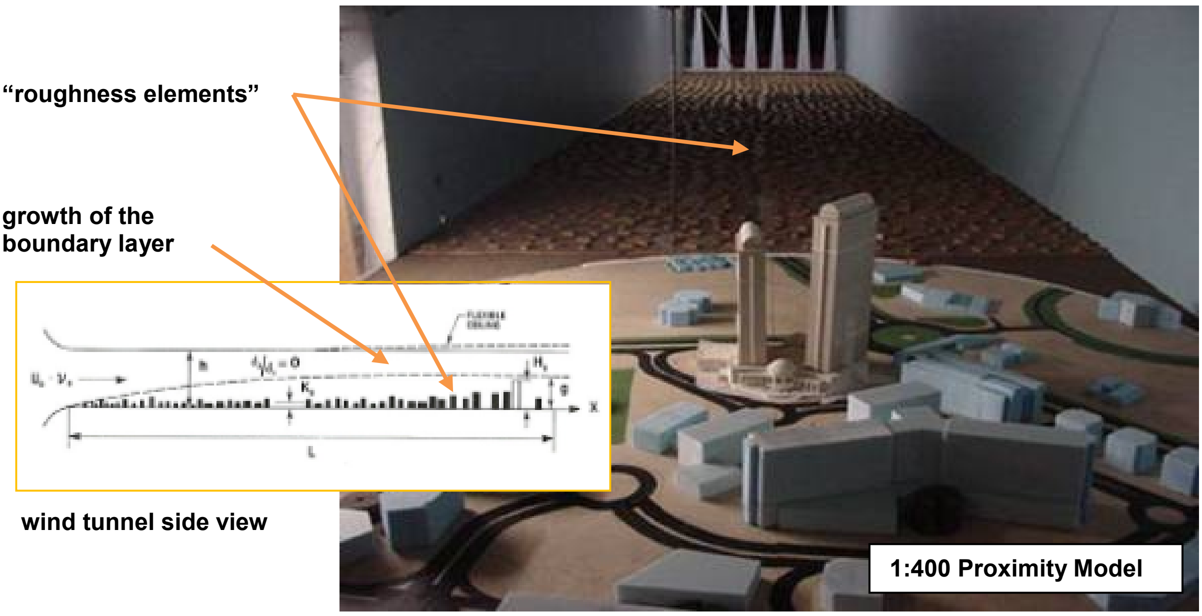
It is an important observation that virtually all of the world's major wind tunnel testing facilities agree with and employ the same basic techniques for wind tunnel testing (model scale parameters, simulation of natural wind, sampling techniques, statistical processing of results, etc).

All wind tunnel tests options have a common start point, namely:

- The use of a physical scaled model to measure the parameters of interest (ground level wind speed, building façade pressure, etc).
  - Accordingly, wind tunnel tests are typically carried out using a **Proximity Model** of all surrounding buildings and terrain covering a circular area just over 1 km in diameter centred on the project site, and with scales close to 1:400.
- The use of a long upwind test section to correctly create the mean wind profile and turbulence intensity specific to the site at the test section where the building model is located
  - This is done via **"roughness elements"** placed along the upwind section of the wind tunnel floor to promote the creation of a boundary layer profile (at model scale) in exactly the same way that real obstacles on the surface of the earth (buildings, trees, etc) create the actual atmospheric boundary layer at the project site.

Both of these features are illustrated in the **proximity model** and upstream **roughness elements** shown in **Figure 44**.

Figure 44 Wind Tunnel Test Proximity Model and Upstream "Roughness" Elements



In terms of studying the wakes behind buildings, three basic wind tunnel testing techniques are available:

- SAND SCOUR, SAND EROSION, OIL STREAKLINE
- DISCRETE SENSOR - using either IRWIN or HOT-WIRE SENSORS
- PARTICLE IMAGING VELOCIMETRY (PIV)

7.2.1 Wind Tunnel Testing Using "Sand Scour", "Sand Erosion", "Oil Streakline"

These techniques involve the same basic principle, namely windflow patterns at ground level can be discerned via the scouring (or "erosion") effect of the wind at low levels, with the greatest scouring occurring at locations of intense wind speed.

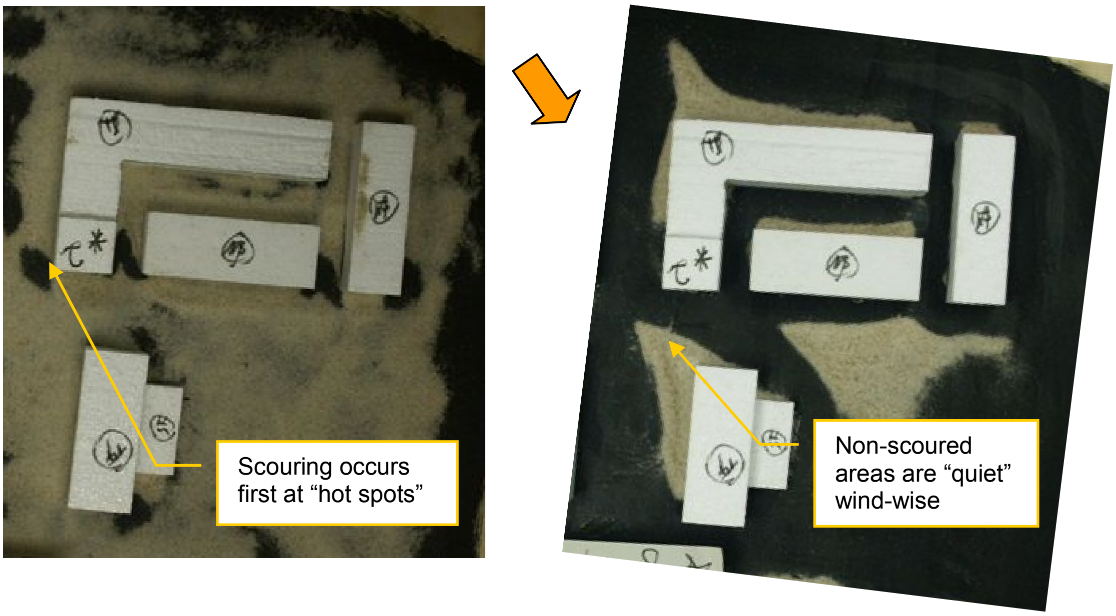
The following outlines the way sand scour / sand erosion testing is carried out:

- A specially chosen scouring material is spread thinly around the model in all areas of interest
- The speed in the wind tunnel is then increased in intervals – corresponding to given full-scale wind speeds, eg 20 kph, 40 kph, 60 kph, 80 kph etc.
- At each speed, the test is allowed to reach a steady-state in terms of scouring.
- The scouring of the material is then observed and photographed (digitally). The photos at each speed are then digitally superimposed on each other to show the expanding scouring pattern.

From numerous previous tests, the wind speed at which scouring occurs has already been calibrated. The results can then be used to develop wind speed contours (and hence "hot spots") OR frequency of occurrence contours of "given" speeds of interest.

These contours can be related to the local wind climate probability distribution to yield the frequency of occurrence of different wind events – ie scouring events - at appropriate probability levels, eg once per week, once per month, once per year, etc.

Figure 45 Sand Scour Examples (a) low wind scour, (b) high wind scour



The reader is referred to the following two excellent technical resources outlining the basis of the technique and validation experiments carried out to demonstrate its effectiveness in identifying wind impacts around building developments.

Livesey, F, Inculet D., Isyumov N., Davenport A.G.
"A scour technique for the evaluation of pedestrian winds",
Journal of Wind Engineering and Industrial Aerodynamics, vol. 36, pp. 779-789, 1990

Gabor Dezso,
"On Assessment of Wind Comfort by Sand Erosion",
Eindhoven University Press, Netherlands, 2006, ISBN 90-6814-602-5.

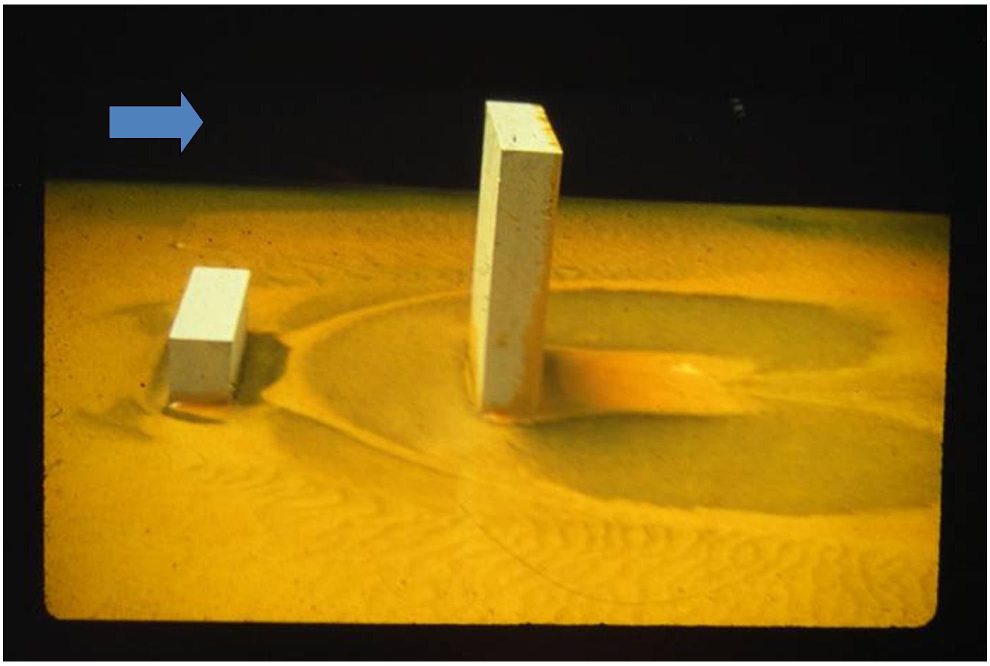
Oil Streaklines

The **sand scour technique** is a similar type of "area" method to the **oil streakline technique** employed by early researchers (such as Beranek) to illustrate windflow patterns around regular shaped buildings. An example is shown in **Figure 46**.

The oil streakline method involves placing a layer of a very viscous mixture of kaolin and paraffin oil on the wind tunnel floor around the building(s) of interest. Under the action of windflow close to the ground, the mixture responds by moving in the direction of the local flow and the paraffin oil evaporates. Such experiments use vivid colours for the mixture to provide highly informative streakline patterns showing the mean direction of the windflow at ground level. With experience, researchers were able to get the actual shapes and features of the streaklines to yield additional information regarding turbulence levels in the flow.

The oil streakline method thus had the added benefit (compared to the sand scour technique) of providing useful directional information regarding low level winds.

Figure 46 Example Oil Streakline Pattern Around Two Buildings



7.2.2 Wind Tunnel Testing – DISCRETE Sensor Tests

"Discrete sensor" tests are carried out using the same 1 km diameter proximity model as all other wind tunnel techniques. In these tests however, discrete sensors are positioned around the building of interest in order to make accurate wind speed measurements at the chosen locations, typically publically accessible areas likely to be prone to adverse winds.

The two most common types of sensors are:

- Irwin Sensors (refer to publication below)

  H.P.A.H. Irwin:
  "A Simple Omnidirectional Sensor for Wind Tunnel Studies of Pedestrian Level Winds",
  National Aeronautical Laboratory, NRC Canada, May 1980.

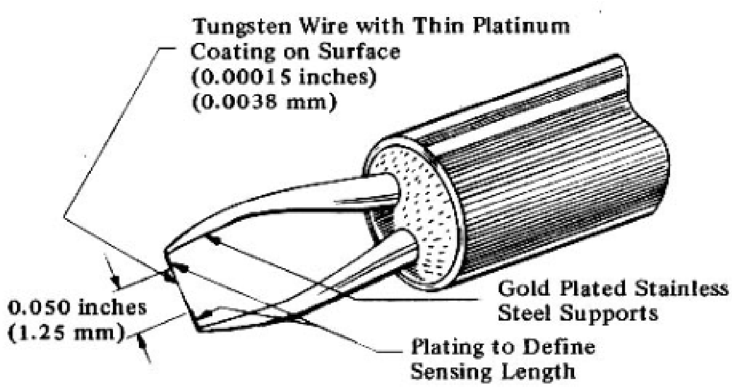
- Hot-Wire Probes

  Refer to manufacturer specifications for operational/calibration information

Hot-wire anemometers have been used for decades in the wind tunnel. They are a powerful research tool in fluid mechanics, able to measure turbulence flow patterns around models of buildings and other bodies of interest (vehicles, airplanes, etc) and within the wakes of blades used in rotational machinery such as wind turbines and radial compressors. Essentially, a hot-wire anemometer is a small, electrically heated element immersed in a fluid for the purpose (usually) of measuring velocity. Hot-wire probes ("hot wires") are constructed so that the temperature of the heated element responds in a highly sensitive manner to the magnitude of the flow passing over the element.

Figure 47 shows a hot-wire anemometer probe. Typical dimensions of the wire sensor are 0.005 mm in diameter and about 1-2 mm long.

Figure 47 Typical Tungsten Hot Wire Sensor and Support Needles



One of the advantages of hot wires is that they can be mounted at the ends of probes which can be positioned to measure wind speeds at any location of interest, eg to identify the extent of the wake behind a building at any height above ground level.

While able to provide highly accurate measurements of mean wind speeds and turbulence levels, hot wires had several considerable practical drawbacks that limited their widespread use. The sensors were relatively expensive (especially in the 1970's and 1980's) and the tungsten wire tips were liable to frequent damage during the normal course of carrying out a wind tunnel test and the. For wind tunnels possessing only one or two hot wire probes, the time it took to obtain meaningful 3-D information regarding flow past a building of interest was considerable and interruptions to testing due to filament breakage common.

These practical difficulties contributed to the development of the Irwin (pressure) sensor – shown in side view in **Figure 48**. The axisymmetric sensor outputs a pressure difference which is related to the wind speed at a chosen height above ground level (of particular relevance to pedestrians). Validation tests were carried out by comparing hot-wire and Irwin sensor data measured at ground level behind square buildings. These showed – refer **Figure 49** - that the sensor can be used to measure both mean speeds and the lower frequency fluctuations of turbulence.

Figure 48 Irwin Sensor – Sectional View

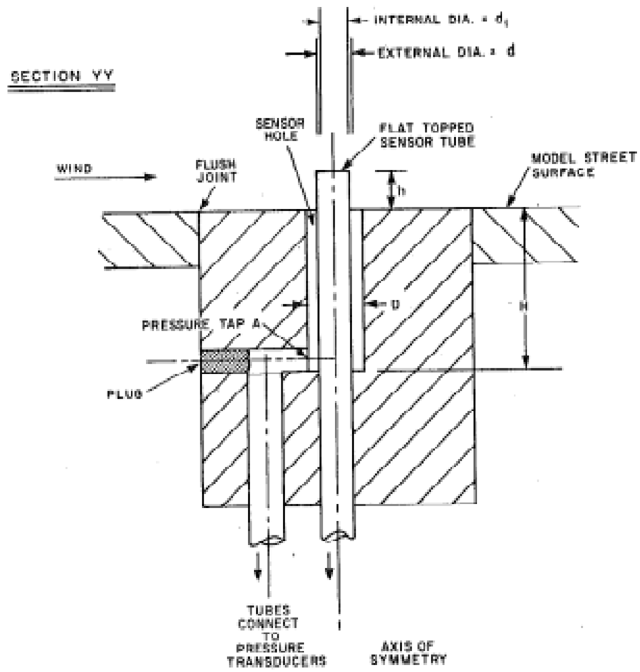
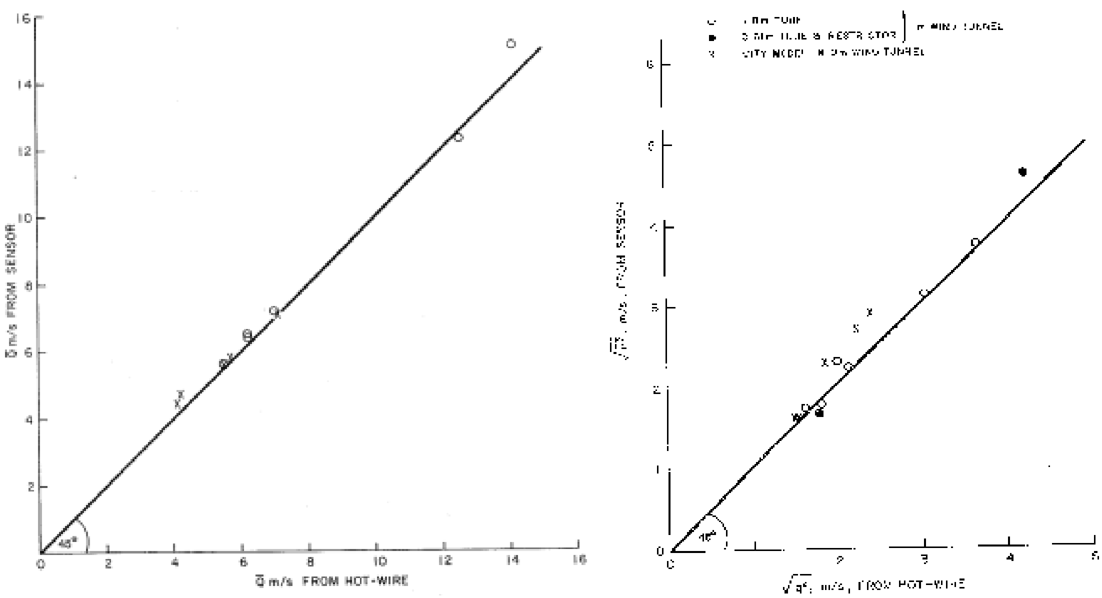


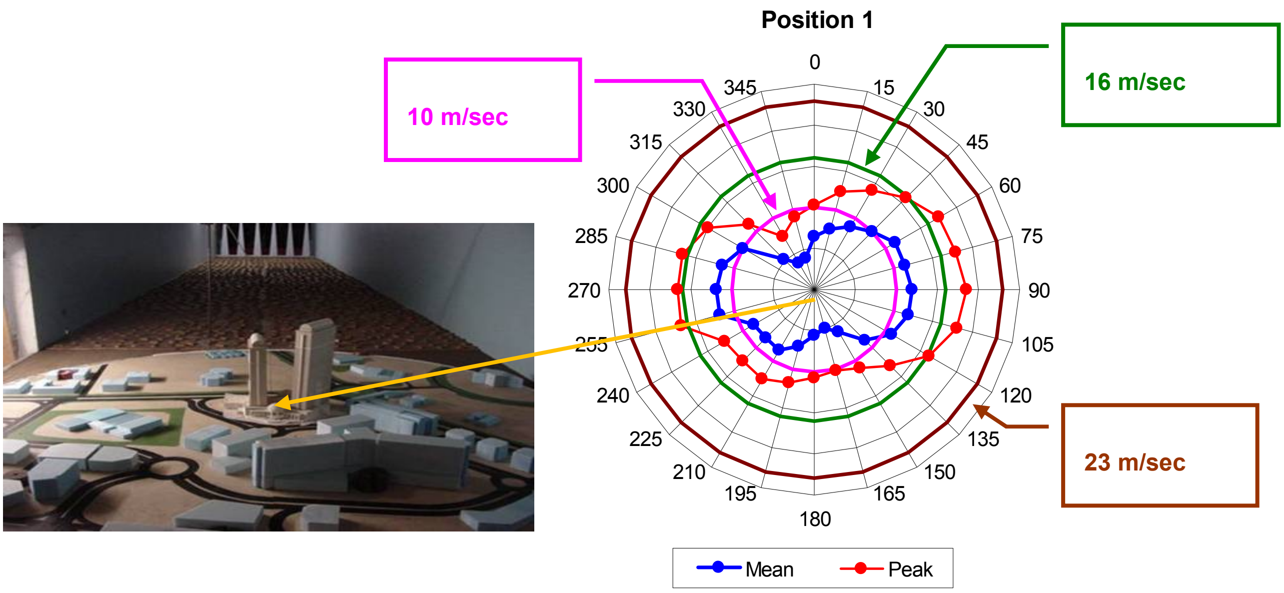
Figure 49 Irwin Sensor Mean (left) and Turbulence (right) Velocity Validation Tests



The output from discrete sensor tests is a series of individual measurements of instantaneous wind speed (mean and gust speed) at each of the chosen sensor locations, equivalent roughly to pedestrian chest height. In a typical pedestrian level wind study, the wind tunnel test data can then be compared with International Criteria for pedestrian and occupant safety and comfort.

A sample Discrete Sensor Test Result at a *"Location 1"* is shown in **Figure 50**. It can be seen that the peak gust winds are strongest at Location 1 from the east and west, where winds were seen to channel in between adjacent tall buildings to the north and south. For other directions, eg north or south, these same buildings provide significant blockage to winds at this location.

Figure 50 Sample Discrete Sensor Wind Tunnel Test Output



Discrete Sensor v Area (Scour) Testing in the Wind Tunnel

Figure 50 highlights both the strengths and limitations of discrete sensor testing as compared to the "area" type of tests carried out using sand scour or oil streaklines.

- **Discrete sensor tests** can provide **highly accurate information** on both mean and turbulent wind speeds **at specific locations**
- The extent of coverage of discrete sensor tests therefore depends upon the consultant choosing a **representative selection of wind monitoring locations** able to characterise the impact of a new development on surrounding winds. There can often be a tendency in discrete sensor testing to select locations likely to be wind "hot spots", eg near building corners, which can lead to an unrepresentative perception of the impact of a development as a whole.
- **Scour-type area tests** on the other hand yield information on the **whole windfield** surrounding a development of interest, which is particularly useful for (a) large multi-building developments and (b) tests where wind speed information is required at large distances from the test building.
- Area type tests however only provide information on the windfield **at ground level** (ie which is fine in so far as pedestrians are concerned)
- Hot-wire discrete sensor testing can provide accurate wind information **at any height** above ground.

Each therefore has their place in terms of the particular goals of a wind tunnel investigation.

7.2.3 Wind Tunnel Testing – PIV (Particle Image Velocimetry)

PIV is a non-intrusive technique for extracting a velocity field (usually in a 2-D plane) from a turbulent windfield. It uses a laser pulse to “illuminate” a 2-D plane section of windflow which can then highlight particle tracers while a camera records their position. A second laser pulse illuminates the same section of windflow a short time later (can set at any time differential from a fraction of a second to many seconds later). The position difference can then be captured from the paired photos and then resolved into their respective velocity components.

In practice, the camera can keep recording digital images over any duration and these images can be “averaged” yielding images of the mean or average windflow in the place of interest. PIV can therefore capture both **instantaneous** windfields and **averaged** windfields and seems particularly well suited to identifying the extent or influence zone of the turbulent wake region behind any building shape of interest.

The following two technical resources describe some very recent experiments and validation studies which demonstrate the effectiveness of the technique in identifying windfield characteristics around building developments.

Brizzi, Poitras & Gagnon,
“PIV Measurements Around 2-D and 3-D Building Models”,
International Journal of Engineering Systems Modelling and Simulation, vol. 1, no 1, 2008

Figure 51 shows the following PIV characteristic outputs take from the Brizzi et al (2008) study:

- The top diagram shows a series of rectangular “sheets” labelled “Zone 1”, “Zone 2”, etc, which are the areas where the PIV cameras are able to capture their windfield information. Each zone represents a 2-D slice where the camera focal lengths are adjusted to capture the “seed” particles introduced into the windflow. The images from each zone then need to be re-combined to enable a compete windfield to emerge.
- The next diagram show the results of capturing velocity field images in a vertical slice taken along the centreline of the building.
- The final (lower two) diagrams show the wake flow behind the building in a vertical slice (a) and a horizontal slice (b). The wake zone is clearly delineated and the wind speed magnitudes within the wake zone clearly identified.

Masters, Gurley, Prevatt, Dixon & Romero,
“Residential Roof Covering Investigation of Wind Resistance of Asphalt Shingles”,
SERRI Project No. 90100, Joint Project by University of Florida and University of Western Ontario.

Figure 52 shows the following taken from the Masters et al (2009) study:

- The top diagram shows the test set-up in the University of Western Ontario’s wind tunnel test facility. The investigation centred around the risks associated with roof shingle uplift during a severe windstorm event (eg a landfalling hurricane). The PIV camera is set up to capture a 2-D slice of windflow on the roof of the test building.
- The next diagram shows the illumination of the test area being captured by the PIV camera.
- The final (lower) diagram showing the u (alongwind) and v (vertical upwards) level of turbulences on the windward (critical) side of the roof. The location and magnitude of the wind “hot spot” at the leading edge of the roof is clearly identified.

From the above, it can be seen that PIV is a powerful tool with few apparent drawbacks, the only one of significance being a need for the PIV camera(s) to be able to “see” the area of windflow of interest. Multiple building configurations therefore represent a challenge to the commonplace application of PIV testing, a situation NOT likely to be encountered for airport-related building wake studies.

Figure 51 Sample PIV Outputs from the Brizzi et al (2008) PIV Study

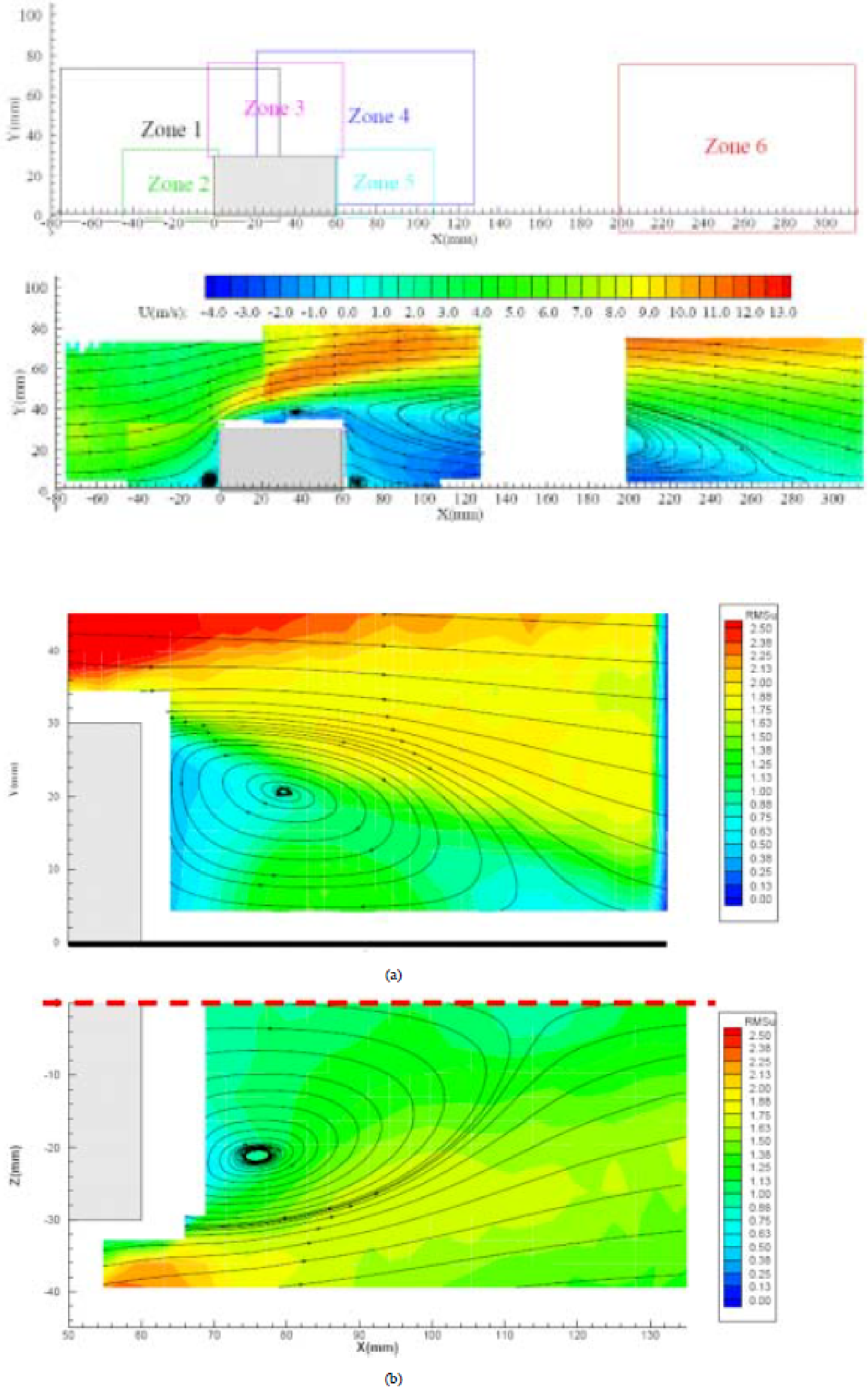
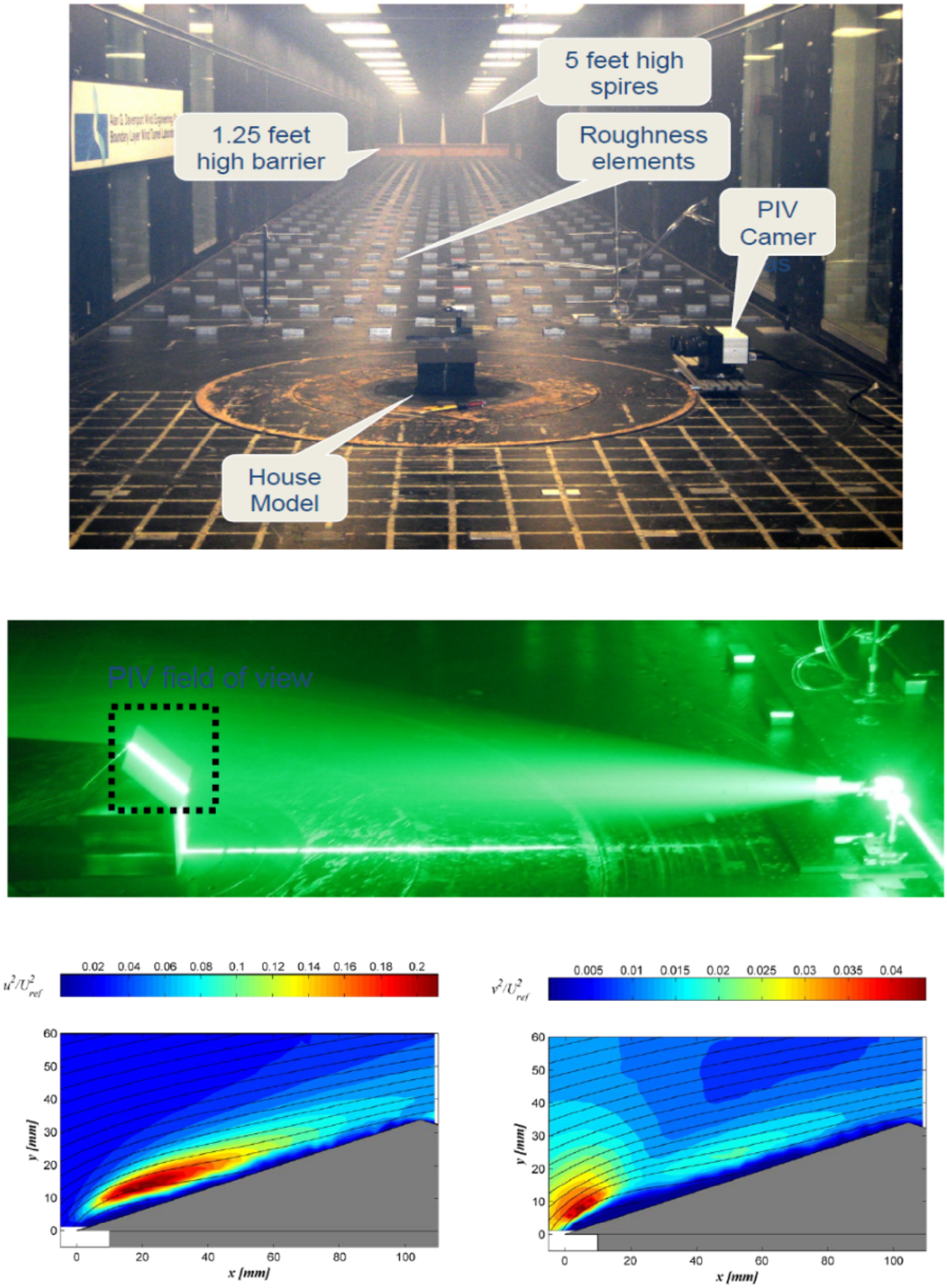


Figure 52 Sample PIV Outputs from the Masters et al (2009) PIV Study



7.3 Comment on the Usefulness of Available Wind Assessment Tools for Building Wake Assessments

In this section, the various assessment techniques for wind assessments have been discussed, namely:

- Qualitative Studies ("Desktop", "Expert Opinion")
- Wind Tunnel Testing Studies (Using Scaled Models of the Building and Wind)
- CFD Modelling Studies (3-D Computer Simulation)

In **Section 6**, building wake characteristics were examined, from which one might reasonably conclude the following:

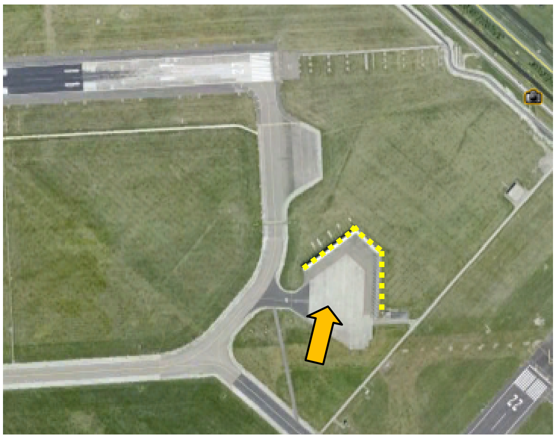
- For regular (ie rectangular) building shapes, there is sufficient information from previous wind tunnel studies (using hot-wire or PIV techniques) and CFD studies to enable an experienced wind engineering consultant to estimate the two primary parameter of interest to this study, namely the magnitude of mean velocity deficit in the building wake as a function of distance downstream.
- **Table 4** (**Section 6**) provided a quantitative means to establish the mean velocity deficit (as a percentage of the upstream unaffected flow) in the wake of a rectangular building where flow re-attachment does not occur.
- **Table 5** (**Section 6**) provided a comparable set of mean velocity deficit estimates, this time as a function of the mean upstream velocity at building height, for buildings in the height range 30 m to 40 m. This is a useful representation as the building height mean velocity can be related to a probability level of occurrence from the wind rose statistics of the local site.

In **Section 6**, it was also noted that **oblique flow situations** give rise to delta-like vortices which can extend to above wake effects many building heights downstream, especially in terms of their turbulence levels. **Non-regular building shapes** also give rise to unexpected wake behaviour.

An example of this is the engine test run facility at Schiphol Airport (refer **Section X**), which is **less than 20 m in height** but has been found to impact inbound flights on the airports runway 27 at a **distance of over 300 m**. At this distance, the mean velocity deficit was found to exceed 7 kt under ambient wind approach conditions varying between 22 kt winds at 220º and 30 kt winds at 240º. Of particular interest was the height of wake disturbance (centred at over 40 m above ground level), attributed to the unusual "U" shaped plan form of the facility.

It is interesting to compare the plan form of the Schiphol engine test facility (left picture) to the general plan form of two newly constructed office buildings at Canberra Airport (right picture).

Figure 53 Examples of Non-Regular "Obstacle" Shapes at Major Airports



7.4 Note Regarding Available Building Wake "Rules"

There are a number of commercially and free-ware available software tools used for example to carry out pollutant transport predictions which carry with them algorithms describing the extent of the wake behind buildings. A recent study by

Petersen, R.,
"Comments on Building and Terrain Downwash Issues",
9th Conference on Air Quality Modelling – A&WMA AB-3

The paper examined potential errors when using the building wake algorithms used for pollutant transport predictions found within the commonly-used AERMOD/PRIME - BPIP algorithms. These use building shape and position information to predict plume behaviour for stacks located in the immediate vicinity of the building of interest.

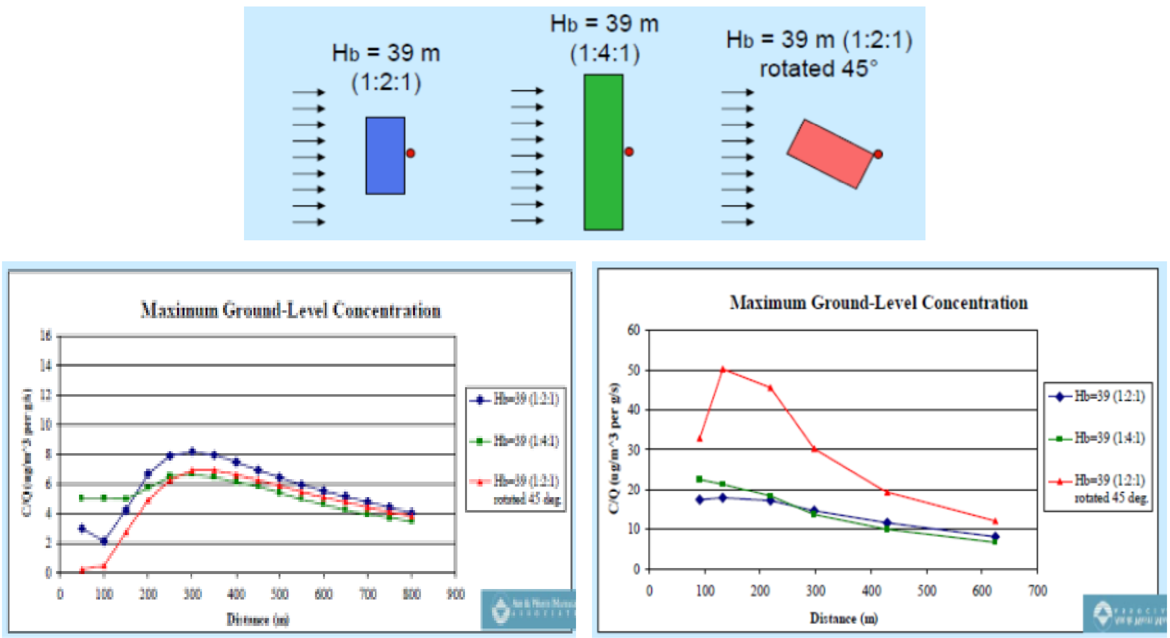
The paper noted that the AERMOD downwash algorithms were designed for **simple rectangular buildings** and even then, only appropriate for **certain building aspect ratios**. The other key observation made was that the AERMOD building wake algorithms did not account for **corner vortex effects** which are known to have a significant impact on the extent of wake disturbance.

The paper selected some typical building dimension configurations of interest and compared the AERMOD predictions with the accurate model scale wind tunnel simulations.

A key set of comparison results is shown in **Figure 54**. Three building configuration were tested including one oblique windflow test (refer upper diagram). The left bottom diagram shows the AERMOD pollutant concentration predictions. The right bottom diagram shows the WIND TUNNEL (more accurate) pollutant concentration predictions. The deviation between the AERMOD and wind tunnel results for the oblique flow case (refer red curves) is clear. In particular, the under-estimation of the AERMOD predictions for the oblique flow case indicates that it was unable to capture the extent of the wake behind the simple rectangular buildings being tested.

The Petersen paper concluded that more research was needed so that AERMOD could capture key wake flow characteristics in the context of several important areas, including the issue of corner vortex induced wake flow for oblique oncoming winds. The paper also shows the value of using quantitative techniques (like wind tunnel testing) to examine wake disturbance.

Figure 54 Comparison of AERMOD and Wind Tunnel Pollutant Concentration Predictions



8 EXAMPLE STUDIES FOR BUILDING WAKE ASSESSMENT

In support of the present study, SLR Consulting undertook three wake flow assessments to determine the extent of the wake behind a building and the magnitude of disturbance to mean wind speeds and turbulence levels in the wake:

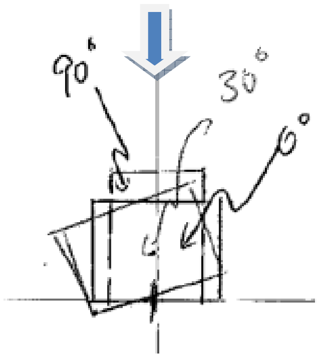
- Wind Tunnel Testing – Using Irwin Sensors
- Wind Tunnel Testing – Using PIV Technology
- CFD Modelling (3-D Computer Simulation)

8.1 Wind Tunnel Study – Irwin Sensors

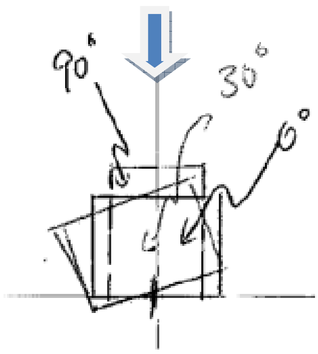
Irwin Sensor tests were carried out on a series of rectangular and complex building shapes for different approach wind angles: 0 °, 30 °, 60 ° and 90° - refer .

Figure 55 Irwin Sensor Wind Tunnel Test Geometries (Length Scale 1:400)

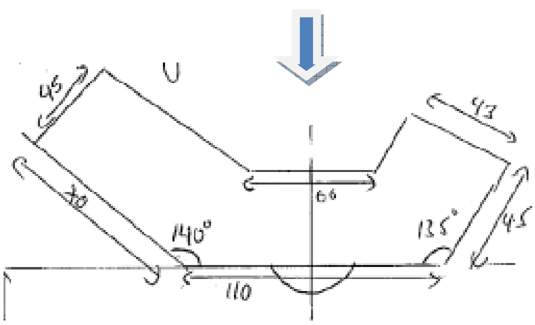
Building Dimensions:
W=200mm, D=150mm, H=75mm



Building Dimensions:
W=150mm, D=75mm, H=200m

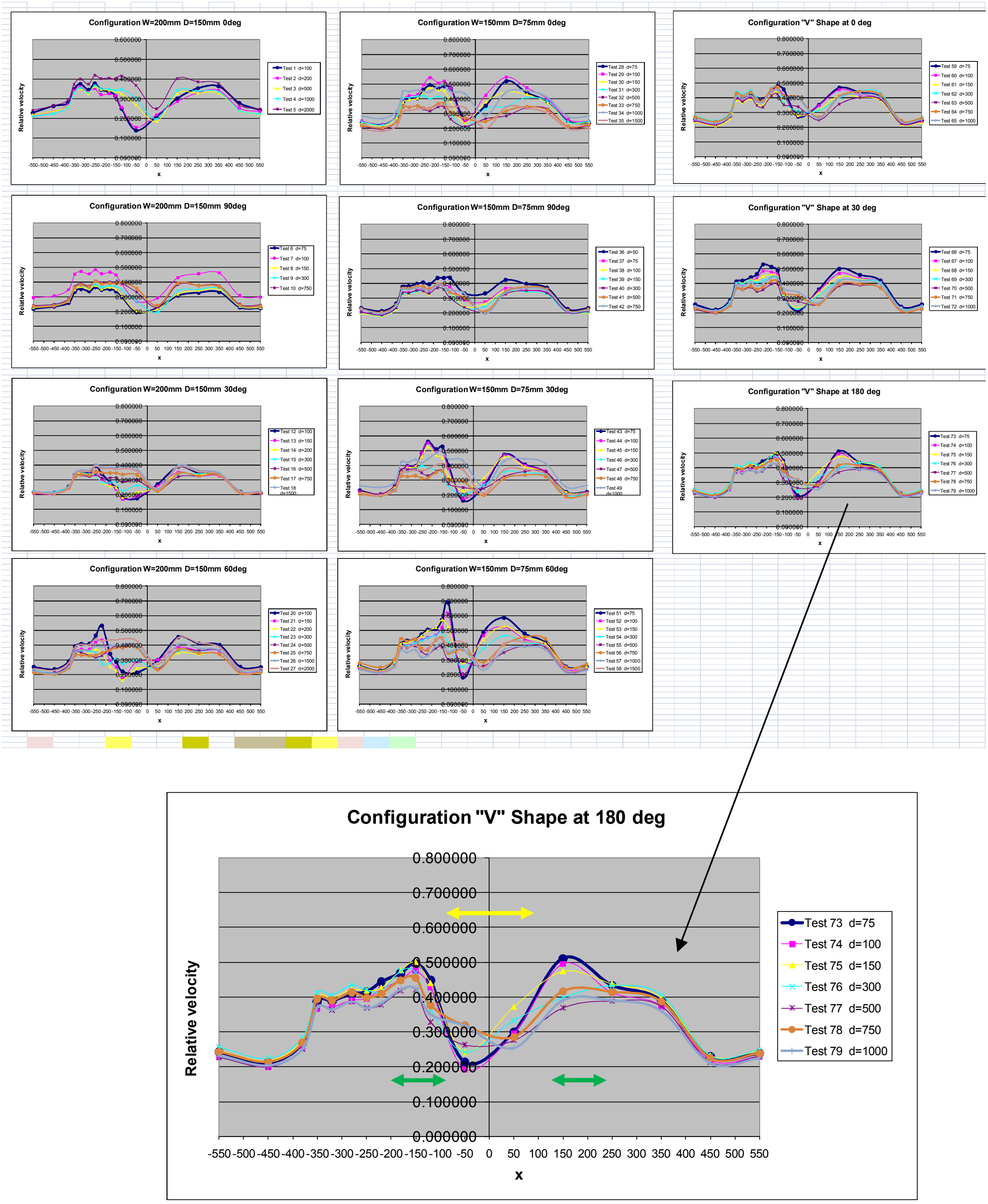


Complex Building
Dimensions as shown:



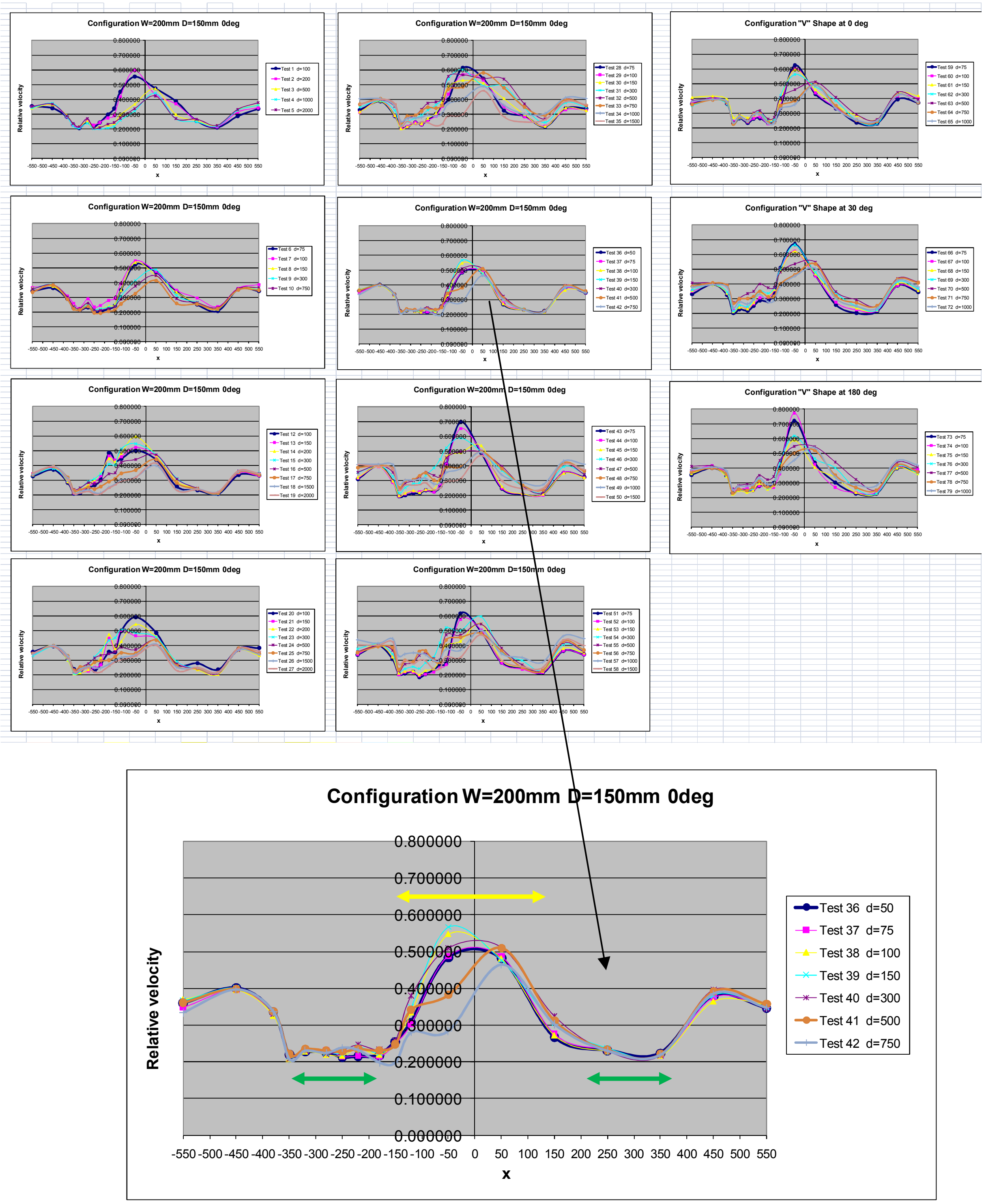
Key results are shown in the **Figure 56** and **Figure 57**.

Figure 56 Irwin Sensor Results – Mean Wind Speeds



The wake region behind the complex shaped building is clearly seen in the area of low mean wind speed (yellow arrow); the shear layer of higher mean wind speed can also be clearly seen (green arrows).

Figure 57 Irwin Sensor Results – Turbulence Intensity



The wake region behind the rectangular building is clearly seen in the area of higher turbulence intensity (yellow arrow); the shear layer of higher mean wind speed (but lower turbulence intensity) can also be clearly seen (green arrows).

8.2 Wind Tunnel Study – PIV Technology

SLR Consulting also carried out a series of PIV tests on two rectangular buildings using the PIV testing technique. Key results are shown in **Figure 58** and **Figure 59**.

Two buildings models were selected

Full-Scale Dimensions	Width = 20 m	Depth = 20 m	Height = 25 m
Model-Scale Dimensions	Width = 100 mm	Depth = 100 mm	Height = 100 mm

The testing was carried out using a CATEGORY 3 type terrain, typical of suburban terrain conditions (trees, primarily low level houses, etc).

A sample set of test results is shown in the following figures:

Figure 59 shows the three wind velocity MEAN components {U,V,W}.

Figure 60 shows the three wind velocity FLUCTUATING components {u',v',w'}.

U-V-W correspond to the crosswind, alongwind and vertical wind directions respectively.

The oncoming mean wind at building height was set nominally at 10 m/s

The middle set of diagrams in **Figure 58** clearly show the extent of the wake bounded by the blue region outside the wake where wind speeds are close to the upwind 10 m/s value.

Figure 58 PIV Test Results – Mean Velocity Components (3-axes)

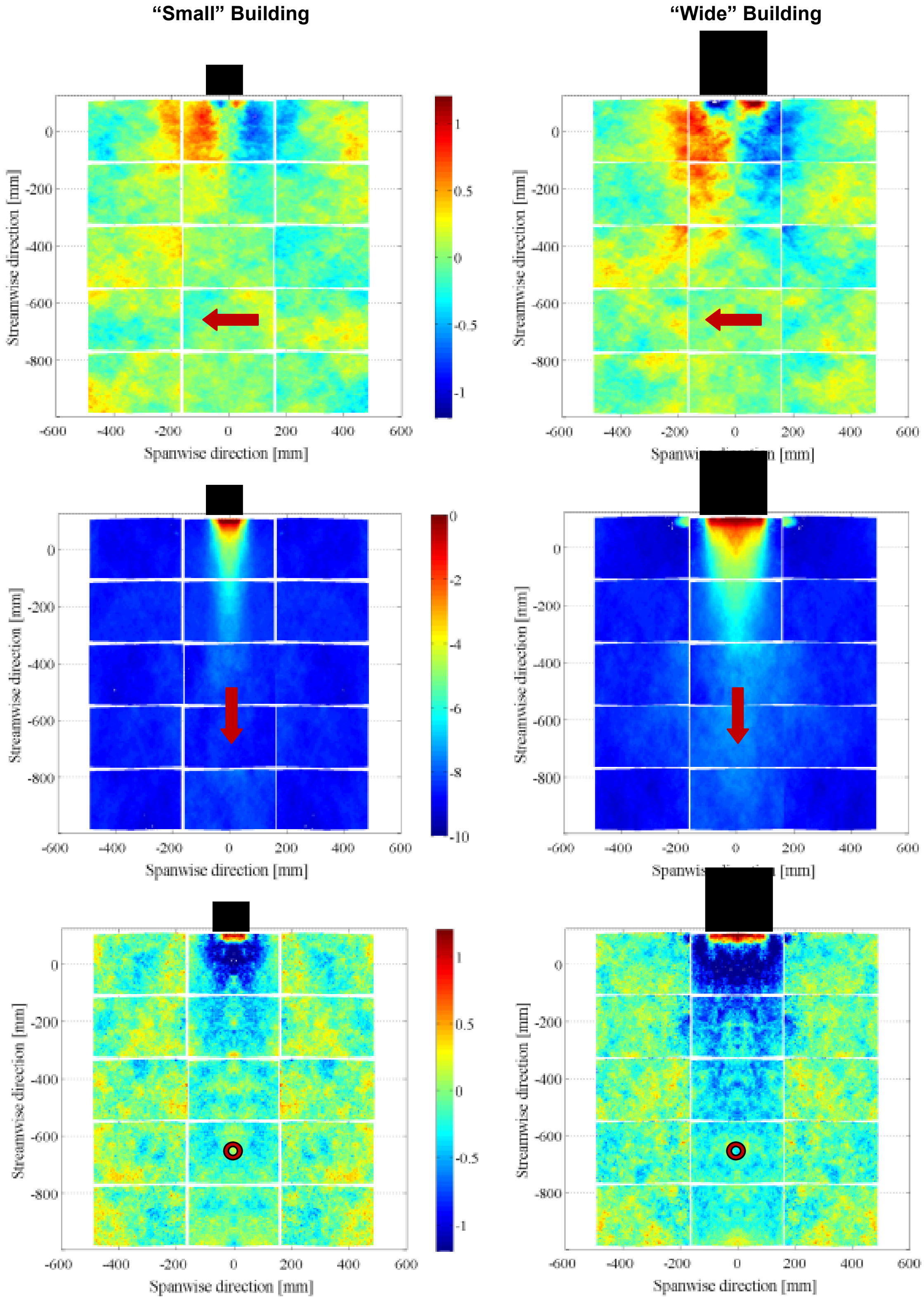
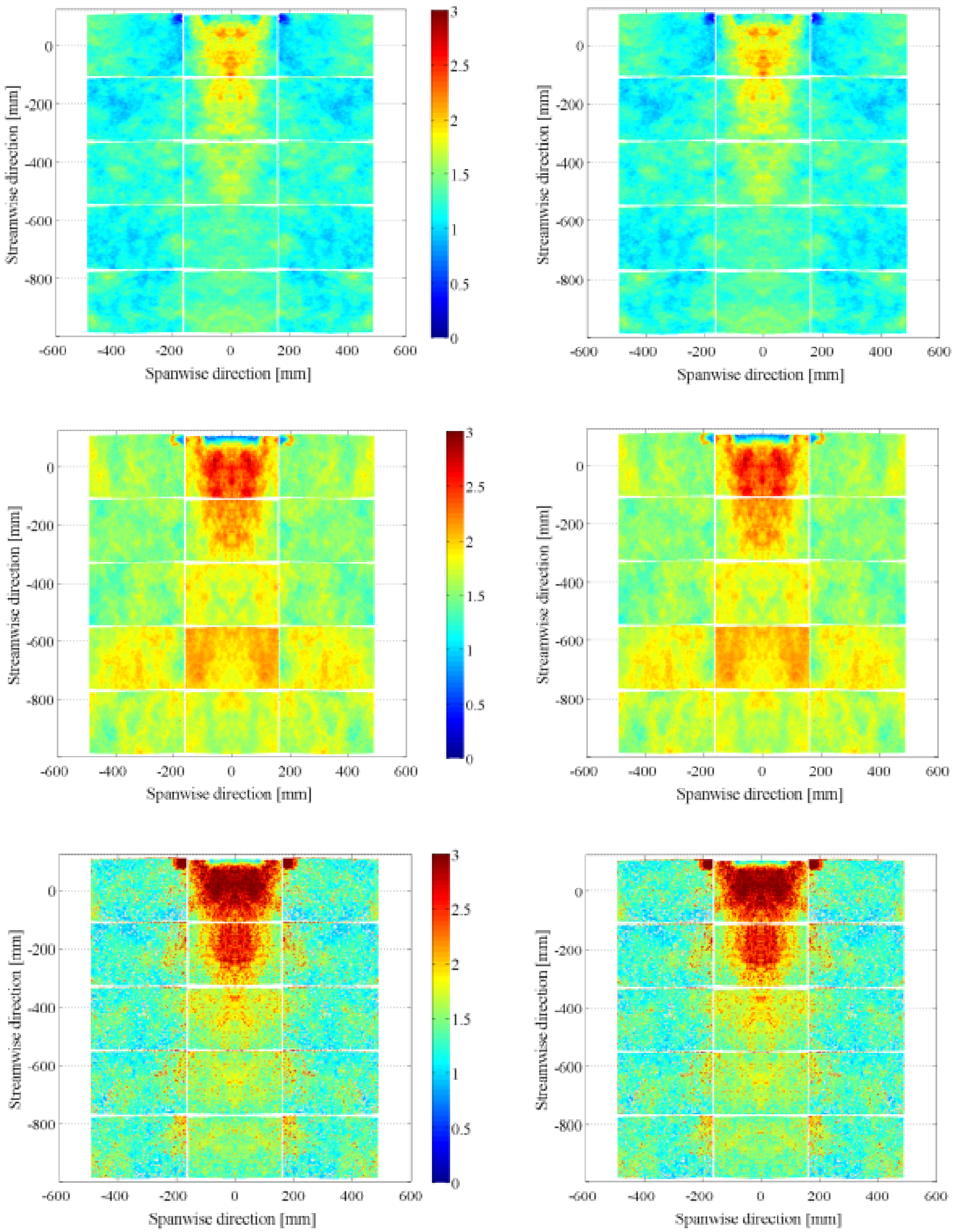


Figure 59 PIV Test Results – Turbulence Level

“Small” Building **“Wide” Building**



8.3 CFD Study

A rectangular building of height, 30 m, and aspect ratio 2:1 (30 m x 60 m) was tested using the CFD technique.

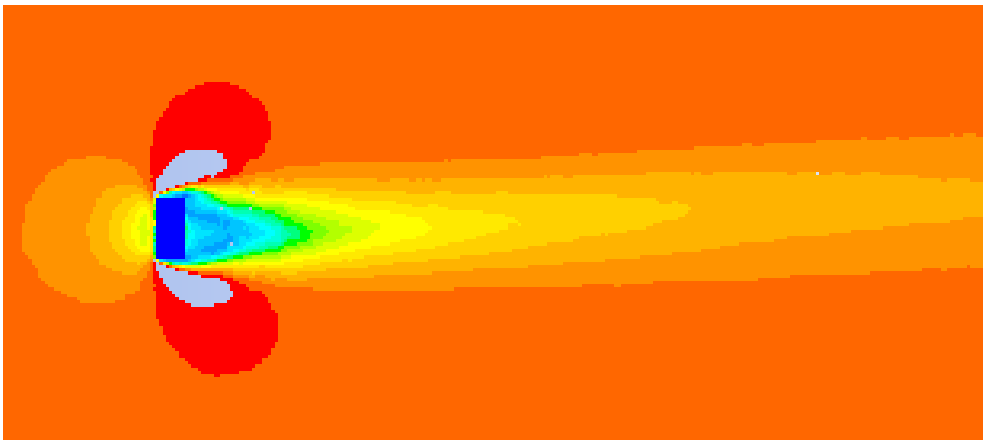
The software package utilised in the current CFD analysis is the commercially available code Fluent. The CFD model solves continuity, energy and momentum equations in the computational domain to predict the steady state airflow inside and around the redevelopment.

- For the current analysis between 4,000,000 to 5,500,000 tetrahedral cells were used to cover the computational domain. Mesh distribution was optimised using Solution Adaptation Technique, eg refining the mesh based on the numerical results for each prevailing wind direction. The following techniques were used for discretization.
- The Reynolds stress model (RSM) was used to solve seven additional transport equations. The model accounts for the effects of swirl, rotation, and rapid changes in strain rate in a more rigorous manner than the conventional one-equation and two-equation turbulence models, it has greater potential to give accurate predictions for complex flows.
- A second order numerical scheme numerical scheme was used for discretization of pressure to obtain more accurate results.
- An iterative procedure was used to estimate the air velocity in terms of three directions, pressure profile and turbulence parameters. For the pressure velocity coupling a global solver based on the SIMPLE algorithm was employed.

Two case studies are illustrated in the figures which follow – Case 1 is for oncoming wind on the broad 60 m face, Case 2 is for oncoming wind on the narrow 30 m face. The upstream wind speed is set at a nominal 10 m/s (the dark orange/red colour).

Horizontal Windfield Close to Ground
(much larger wake disturbance region in Case 1)

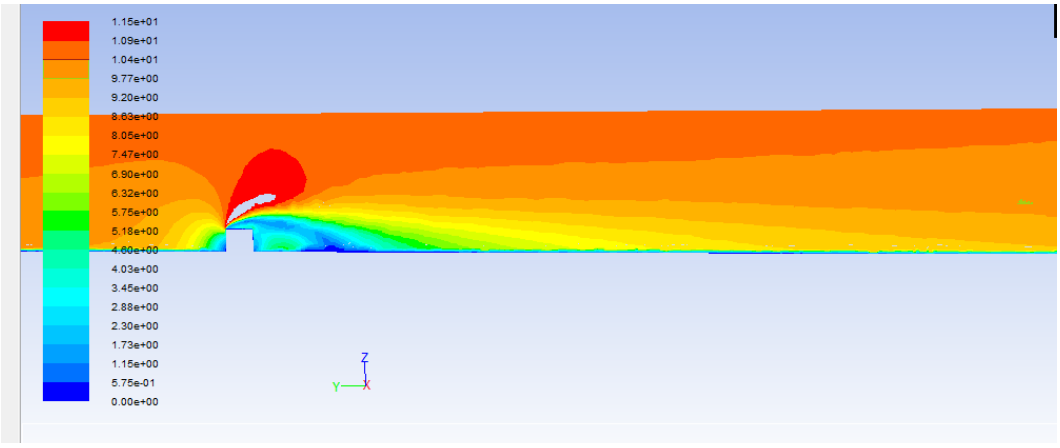
CASE 1



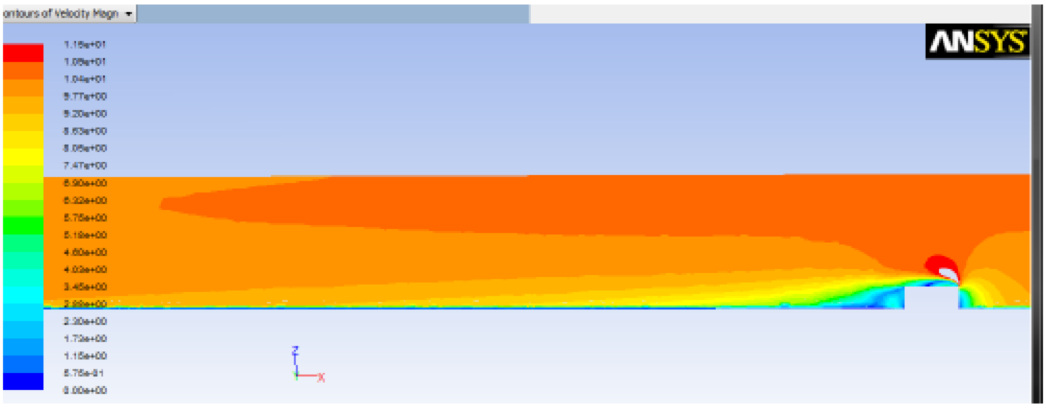
CASE 2

Vertical Windfield Through Building Centreline
(much larger wake disturbance region in Case 1)

CASE 1

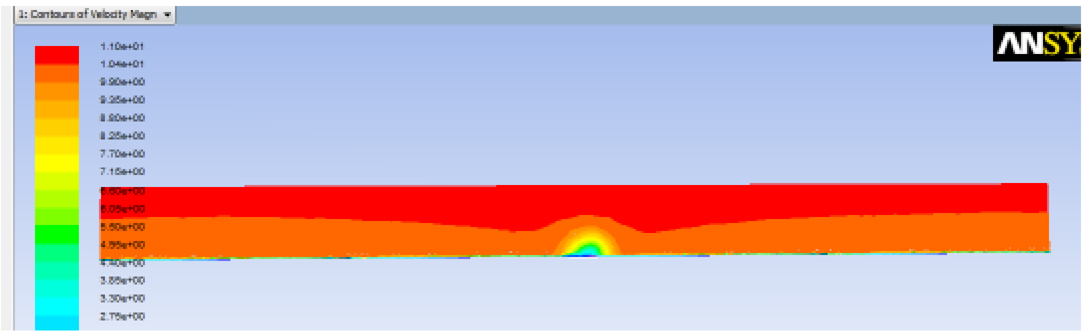


CASE 2

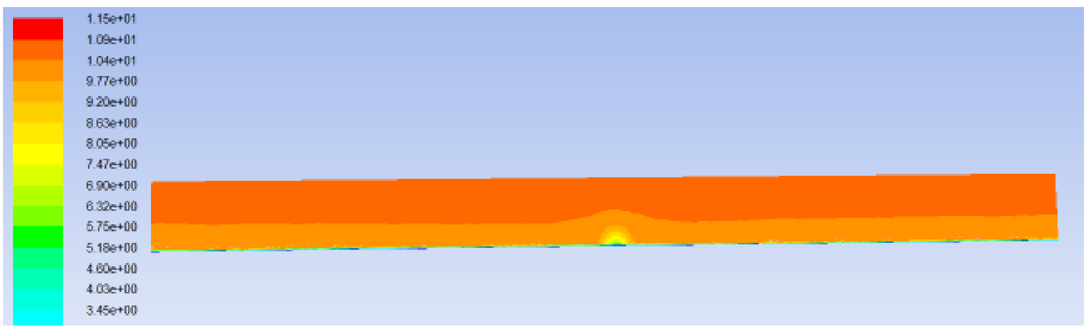


Vertical Windfield at 5 x Building Height Downstream (perpendicular to wind)
(much larger wake disturbance region in Case 1)

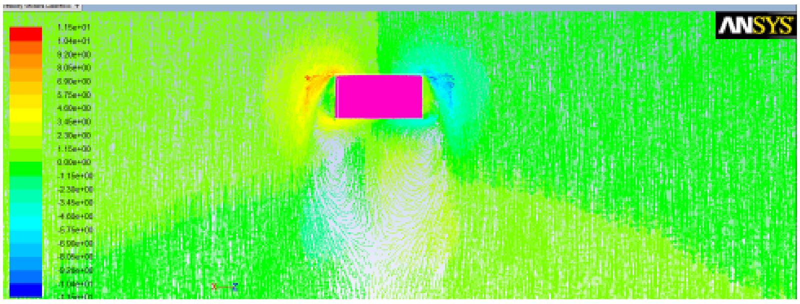
CASE 1



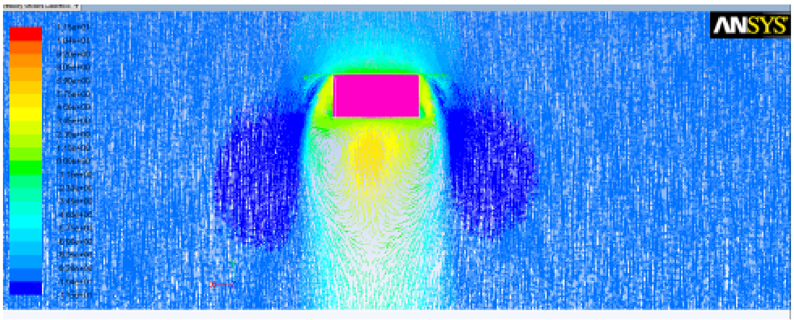
CASE 2



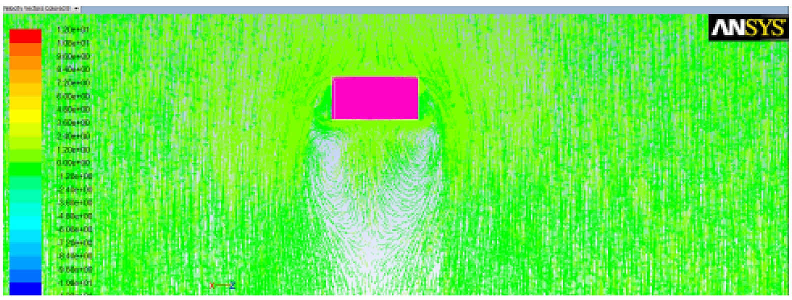
The following graphics illustrate the power of the CFD to distinguish the three wind vectors within the wake flow and identify the turbulence zone above the building. Once again, the extent of wake flow disturbance is clearly delineated.



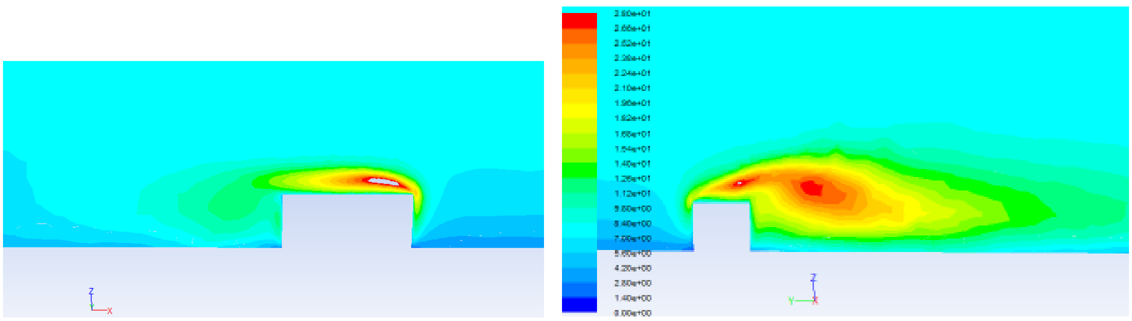
X-Velocity (2D Section Through the Roof) – sideways flow



Y-Velocity (2D Section Through the Roof) – velocity in line with the flow



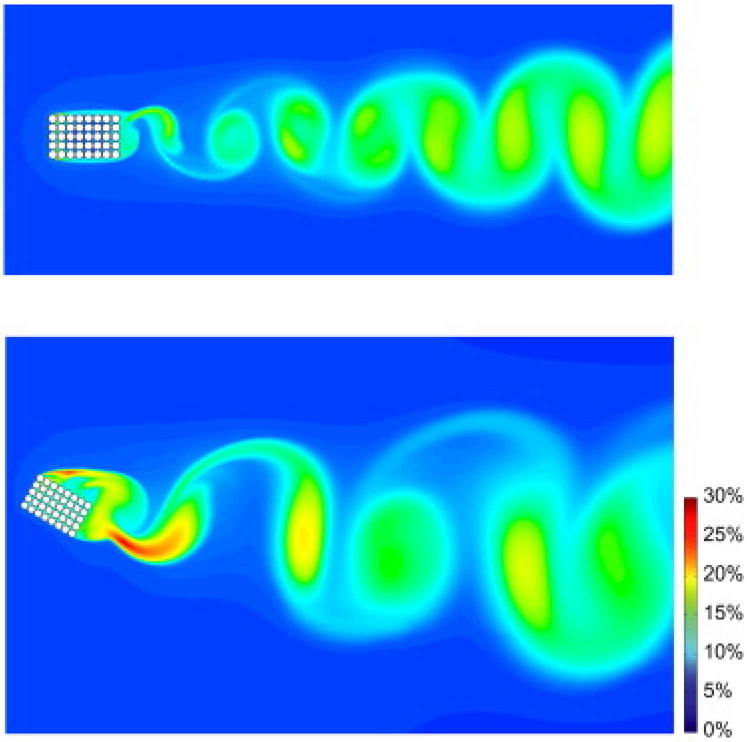
Z-Velocity (2D Section Through the Roof) – vertical flow



Turbulent Intensity in a vertical cross-section through the middle of each building

In the figures below, a comparison was made between the vortex shedding behind a rectangular grid of vertical cylinders oriented (a) perpendicular to the flow and (b) at an oblique angle.

The change in wake width for the oblique flow case is apparent.



(a)

(b)

8.4 Comments

All of the above studies provide reliable quantitative information regarding the extent of wake disturbance behind the buildings investigated.

When combined with windrose information giving the probability occurrence of wind speed at a certain magnitude and from a given wind direction, it is then possible to **reliably predict** the likelihood that a given windshear criterion (eg the Schiphol “7/6-knot” criterion) is exceeded or not.

PART C

Guidance Regarding the Design and Positioning of Structures in Relation to Runways to Minimise Impacts on Aircraft Operations

9 AUSTRALIA'S AVIATION REGULATORY FRAMEWORK

The reader is referred to **Attachment C** for a discussion of the regulatory framework covering aviation safety in Australia and Building Height Restrictions so that subsequent recommendations made in this report dealing with building-induced windshear can be put into context. The optics covered include:

Section C1 CAA, CASA, MOS, CASR, AC, AIP, ERSA, OLS

Section C2 Responsibilities of an Aerodrome Operator

Section C3 Management of Obstacles at Aerodromes

Section C4 General Guidance Regarding Obstacle Management

Section C5 Critical Aerodrome Dimensions Relevant to the OLS

Section C6 Obstacle Limitation Surfaces (OLS)

Section C7 Shielded Obstacles

Of particular interest to the issue of building-induced windshear is the section of **OLS** adjacent and perpendicular to the ends of a runway (where the associated crosswind disturbance is most critical).

A sectional view of the OLS for a type "4E" runway classification is shown in **Figure 59** – refer **Attachment C** for derivation of critical "4E" dimensions. It may be noted that the height of the Inner Horizontal Surface is 45 m for ALL airport code numbers.

Two transitional surfaces are shown in **Figure 59**, one for a "4E" precision approach runway (solid "brown" line) with a runway strip width of 300 m, the other (dashed "brown" line) for a runway width strip of 150 m applicable to non-precision approach runways.

Figure 59 also shows two alternative limiting surfaces, a plane of slope 1:35 out from the runway centreline (labelled the "Schiphol" boundary) and a plane of slope 1:10 out from the runway centreline (labelled the "SACL" boundary).

Finally three solid black lines indicate the nearest distance from runway and height of three "obstacles" of interest to this study:

(a) Majura Park buildings located close to runway 12 at Canberra Airport,

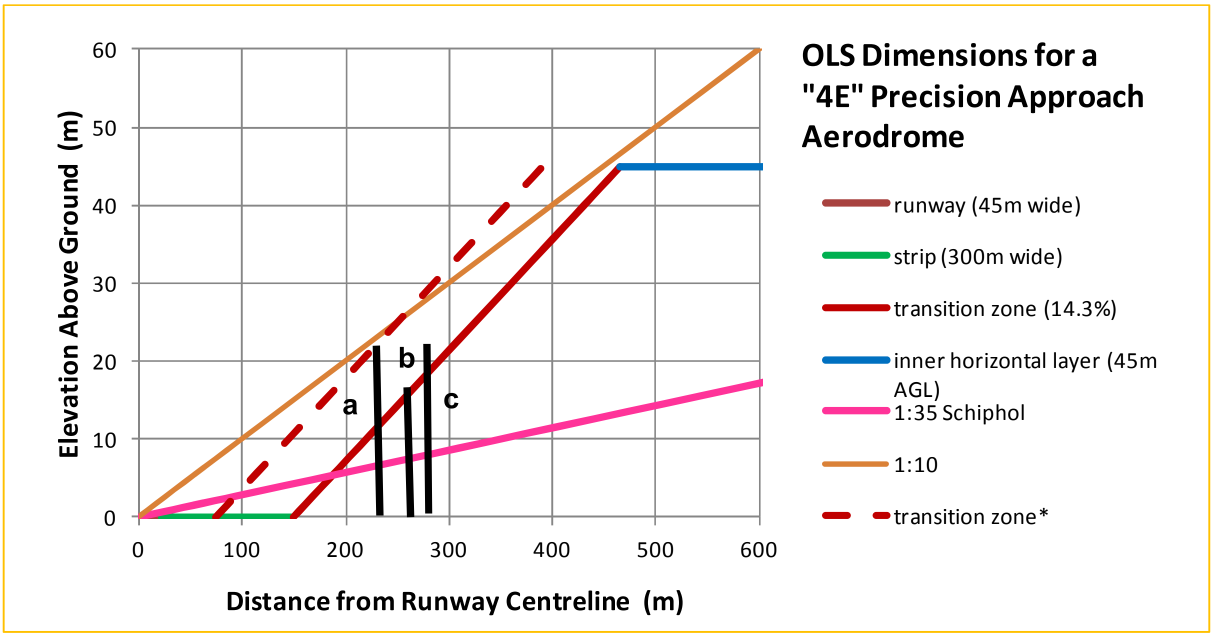
(b) the engine test run facility located close to runway 27 at Schiphol Airport, and

(c) Hangar building located close to runway 35 at Canberra Airport.

From information provided in other sections of this report, it can be seen that ALL of these obstacles - (a), (b) and (c) - have generated documented incidents associated with building-induced windshear (and turbulence).

It is also noted that all three buildings satisfied the 1:10 "simple" building height "rule" currently being used at a number of Australian airports.

Figure 60 Close-up View of Inner Parts of the OLS



10 BUILDING GUIDANCE IN RELATION TO WINDSHEAR IMPACT MITIGATION

In this section, guidance is provided regarding the design and positioning of buildings located within airport precincts aimed at minimising adverse impacts (due to windshear and turbulence) on airport operations.

10.1 OLS Criteria

In **Attachment C**, the "OLS" rules governing the positioning of buildings within certain distances from runways is discussed. It is noted that these are essentially "international" in their nature, ie the same rules, governed by the ICAO, are found at all international airports.

10.2 Generic Building Guidance

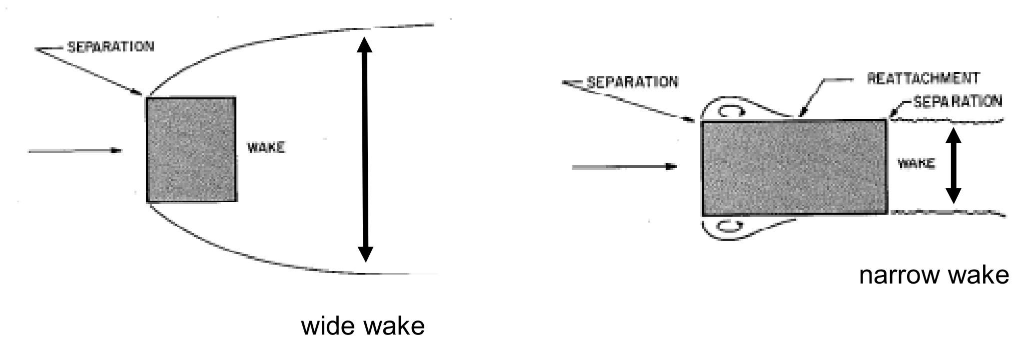
Information derived from mainly wind tunnel testing discussed in **Section 6** has illustrated some key design principles in relation to wake disturbance minimisation and building shape and orientation.

Building Plan Form Aspect Ratio

It has been well documented that the wake behind a building varies significantly with building (plan form) aspect ratio. A building with depth (the dimension in line with the wind) greater than width (dimension perpendicular to the wind), say by a factor of around 2:1, has a considerably smaller wake than a building whose width is equal to or greater than its depth. This is illustrated in **Figure 61**.

For buildings located at an oblique angle to the wind direction, a general rule for the building wake is to assume that it is 1.5 times the dimension of the building as seen from the direction of the wind.

Figure 61 Influence of Building Plan Form Aspect Ratio on Wake Magnitude



Oblique Angle Delta Vortex Vortices

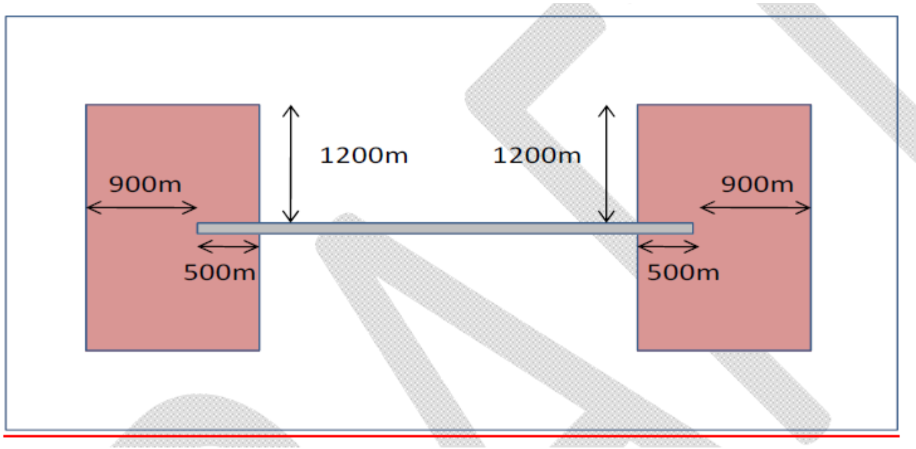
Section 6 also discussed the phenomenon of "delta" vortices which form over sharp-edged rectangular buildings subject to oblique flow, ie oncoming flow at an angle of around 45º to the main façade orientations.

As a general rule, the potential allowable height of a building located close to a runway could be unnecessarily restricted if its orientation is at 45º to the orientation of a nearby runway or where the potential for delta vortex formation is aligned with a prevailing wind direction.

Building Location With Respect to the Runway

Clearly, the instability which **building-induced** wake effects can cause an aircraft is significantly reduced once the airplane has touched down (upon landing) or is at reasonable height (say several hundred metres off the ground (after take-off).

There is therefore a critical zone (in plan view) for building positioning with respect to potential building-induced wake effect problems which needs to be taken into account, namely close to the ends of the runway where a straight line from the building to the runway glide path intersects with an aircraft landing or take-off height near the ground – refer below.



Complexity of Building Shape

In general, buildings at airports have historically tended to take a fairly rectangular form, eg hangars, warehouse type buildings, standard office buildings, etc.

This is not always the case however and this report has highlighted the variations which can occur in wake disturbance for complex building shapes compared to simple rectangular forms. The unusual extent of wake disturbance of the Schiphol engine test facility is an example.

It is not a coincidence that most of the existing quantitative information on wake disturbance gained from wind tunnel testing or CFD studies has involved simple rectangular shapes.

On this basis, it will generally be difficult for even an experienced wind engineer to reliably predict the extent of a building wake when confronted with complex geometry unless a significant degree of conservatism is employed.

Concept of Probability of Occurrence

Finally, it is well understood that building-induced wake effect "events" involve a coincidence of factors including the following:

- There would need to be a building of shape and size able to generate wake disturbances large enough to exceed accepted windshear criteria, eg the Schiphol "7/6-knot criteria".
- The wind would need to be blowing in a more or less cross-wind orientation to the runway being used – this in itself would be somewhat unusual.

The above suggests that the actual risk of a building-induced windshear event should involve statistical analysis indicating the likelihood of occurrence of adverse events so that an informed decision can be made as to actual risk involved.

10.3 Recommended Methodology

On the basis of the above, the following is concluded:

Premise

A wind consultant is asked to provide guidance on the acceptability or otherwise of a proposed building development in relation to the potential wake disturbance caused by the building on nearby runway operations.

Acceptability Criterion

The above premise comes down the question of whether a given adopted acceptance criterion, such as the Schiphol "7/6-knot criteria", will be exceeded or not, and, if it is predicted to be exceeded, how often.

Key Factors to Consider

The key parameters of interest will be:

- **Building Shape** (regular or non-regular)
- **Building Dimensions** (width, depth, height)
- **Perpendicular Distance of the Building from the Runway**
- **Building Position Relative to Touchdown Position**
- **Surrounding Terrain – open, suburban, etc.**
- **Probability of Occurrence and Strength of Winds**
  (magnitude of winds from a direction able to cause a crosswind conditions of concern)

Risk Classification

Using the information assembled in previous sections, the recommended approach is summarised in **Table 4** based on risk categories.

In this instance, a tiered approach has been developed.

ANY building satisfying the Schiphol "1:35 height rule" is automatically acceptable.

If a building lies within the 1:35 height regime, the assessment moves on to the next available assessment approach, termed Categories B1, B2 and C in **Table 4**.

It should be stressed that, with the exception of the 1:35 rule, the remaining assessment types are not strict pass/fail "tests" but require a probabilistic analysis to produce a final result – refer subsequent discussion and **Figure 61**.

Finally, the influence of ambient turbulence levels (regardless of the presence of an obstacle building) should also be considered in line with general aviation criteria for heavy turbulence.

Table 5 Recommended Assessment Methodology Hierarchy

Category	Building Description	Assessment Methodology
Case A	Any Building Shape and The building location satisfies the “1:35 rule”	In this instance, the building is deemed automatically acceptable and **no further assessment is required**.
If a building does not satisfy the 1:35 rule, go on to assessment rules B1, B2 and C and apply a statistical analysis to establish relevant risk levels.		
Case B1	Single, Regular Shape eg Rectangular Buildings Prevailing Wind-Building Angle Perpendicular to Building Facades	In this instance, all available techniques, including a Qualitative (Desktop) Study, could be used to address the acceptability of the proposal. The mean velocity deficit data provided in **Table 3** (**Section 4**) could be used in conjunction with the building height and local wind rose information to identify the potential (if any) for adverse crosswind conditions.
Case B2	Single, Regular Shape eg Rectangular Buildings Prevailing Wind-Building Angle Oblique to Building Facades	In this instance, a safety margin would need to be added to the mean velocity deficit data provided in **Table 3** (**Section 4**) in conjunction with the building height and local wind rose information to identify the potential (if any) for adverse crosswind conditions. The safety margin might be in the form of an increase in perceived distance downstream of the order of at least 25%. The wake width also needs to be adjusted however and this may balance the influence of increased (delta-vortex induced) wake effects, given that wake widths would typically be narrower than for perpendicular wind angles.
Case C	Complex Building Shape Multiple Buildings	In this instance, unless a very conservative safety margin is added to the mean velocity deficit data provided in **Table 5** (**Section 4**), one of the Quantitative techniques described in **Section 7** should be used - Wind Tunnel Hot-Wire, Wind Tunnel PIV or CFD – to establish the likelihood of a potential windshear problem.

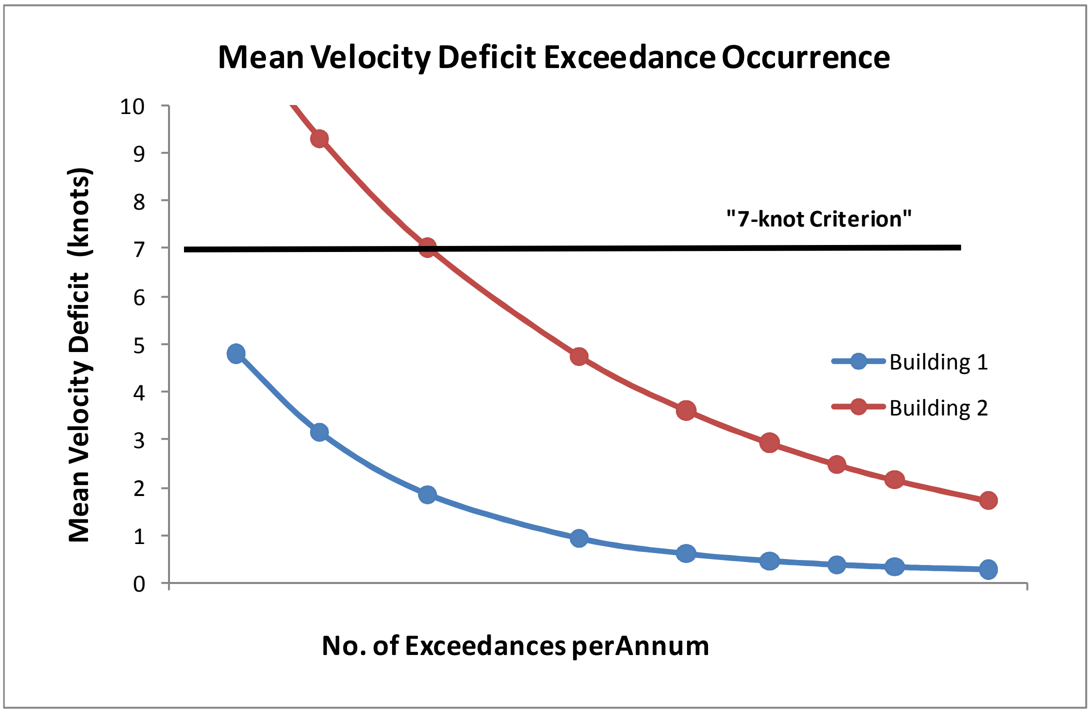
Form of the Output for Assessment

If the building does not satisfy the 1:35 height rule, the output of the consultant's wind assessment will typically be of the form displayed in **Figure 62**.

In this example, two buildings were examined which did not automatically satisfy the "1:35 building height" rule.

- For Building #1, the Schiphol "7-knot criterion" is never exceeded
  - The building is therefore accepted with no consent conditions required to be specified in terms of airport operations etc, eg ERSA wording.
- For Building #2, the Schiphol "7-knot criterion" is exceeded a number of times per year
  - The number of exceedances will now play a role in terms of the consent process for the development.
  - If the predicted number of annual exceedances is **low** (eg several exceedances per year only), the building may still be approved but with a Building Wake Management Plan required. Such a plan would specify a critical ambient wind condition (eg mean winds exceeding "V_{crit}" m/sec and blowing from "θ_{crit}" ±22.5º) under which landings or takeoffs on a particular runway are disallowed.
  - If the predicted number of annual exceedances is **significant** (eg frequent exceedances per year), the building design may require amendment to be approved, eg lower the building height, add edge details which can reduce the extent of the wake disturbance behind the building, etc.

Figure 62 Sample Output for Wind Assessment



10.4 Alternative Methodologies for Building Wake Impact Assessments

A simple "dimensional" rule for assessing the acceptability or otherwise of building projects would have obvious significant cost and timing advantages, by obviating the need for detailed wind assessments.

In fact, one such rule already exists which buildings have to comply with in any case, namely, the OLS requirements mandated under CASA's MOS Part 139 (refer **Section X**).

There is now sufficient evidence by way of aviation incident reports and wind tunnel and CFD studies which suggest that **OLS-defined surfaces are not sufficient** to prevent hazardous levels of building-induced windshear in all circumstances.

Could a simple "height multiplier" rule be effective ?

Examples of such rules are the Schiphol 1:35 rule or a less conservative 1:10 rule - where the ratio is taken to be the height of the building of interest compared to the distance from the runway centreline.

On the basis of the building wake characteristics examined in this study and, once again, aviation incident reports wind tunnel and CFD studies, it is likely that such a rule would have to be **highly conservative** to capture a reasonable range of potential building shapes and configurations.

While easy to apply, such a conservative rule would probably exclude a large number of developments which, under careful assessment, might have easily passed the acceptance criteria adopted in this study.

Should the adopted rules be varied by aircraft type ?

It is certainly true that different aircraft types respond more or less readily to challenging wind conditions. However the adopted criteria stem from the Schiphol "7/6-knot criteria" which were developed for two aircraft types of widely differing weight and inertia characteristics. Consideration has been given to whether the criteria should be varied for light aircraft. There does not appear enough justification for such variation at the present time.

PART D

Guidance Regarding Options to Mitigate Windshear and Turbulence Impacts of Existing Structures

Section 11 Mitigation Options for Existing Buildings

11 MITIGATION OPTIONS FOR EXISTING BUILDINGS

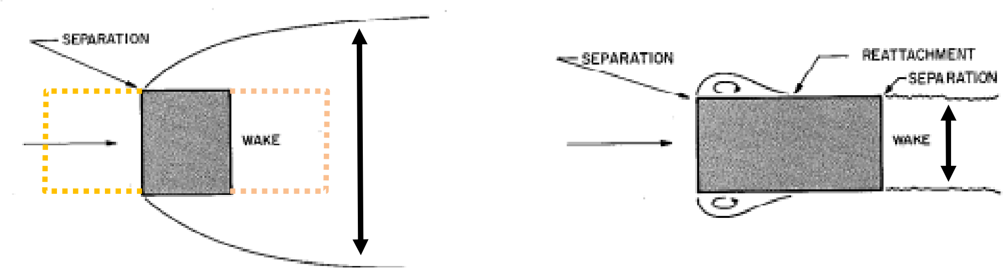
In this section, guidance is provided on options to mitigate building generated turbulence and windshear for existing structures where safety risks are identified.

11.1 Building Shape Augmentation

Reference is made once again to one of the key features which influences the wake flow (and hence associated windshear) behaviour surrounding rectangular buildings, namely building plan form aspect ratio, as illustrated depicted in **Figure 63**

The wake behind a building whose depth (the dimension in line with the wind) is greater than its width (dimension perpendicular to the wind) by a factor of 2:1 has a considerably smaller wake than a building whose width is equal to or greater than its depth.

Figure 63 Wake Flow Characteristics Influence of Building Plan Form Aspect Ratio



Can an existing building which has a "poor" width to depth ratio be improved in terms of lessening its wake impact ? The implied solution here would be to "create" the conditions where the building appears to have greater depth than is otherwise the case, eg to increase the building depth a shown by the orange or pink dotted lines in **Figure 63**. In many instances, the runway (leeward) side of the building would be an area reserved for airport operations and the opposite (windward) side might be needed for building access.

Accordingly, the "orange/pink" building augmentation options is unlikely to be practical in most specific applications.

11.2 Vortex Suppression – Shroud Concept

Reference is made to the following study:

Wong, H.Y.
"The Suppression of the Effects of Vortices"",
University of Glasgow (Scotland).

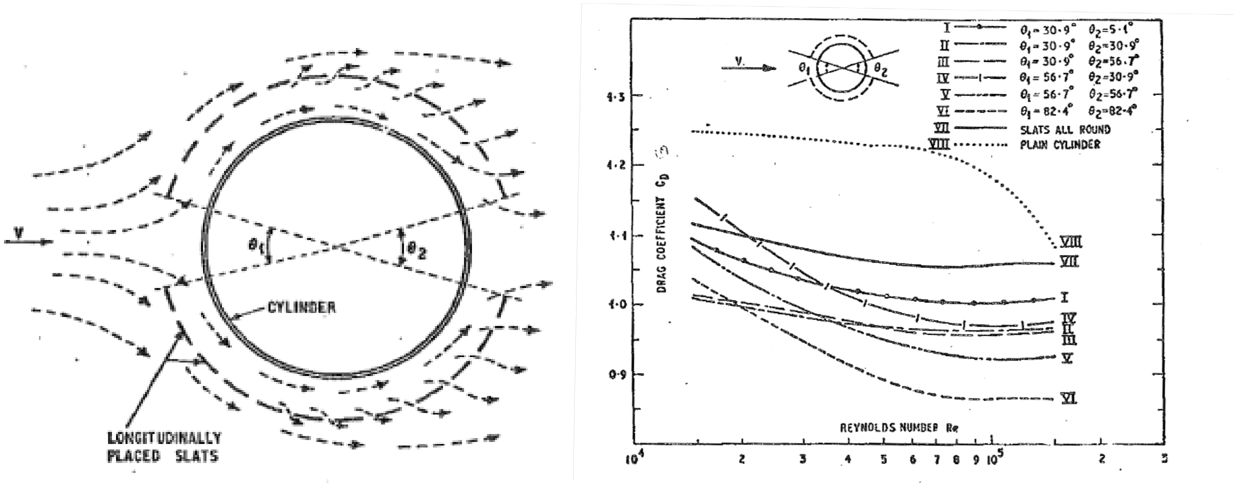
Over many years, aerodynamic devices have been developed to mitigate the impact of vortex formation behind structures, especially taller lightweight buildings and towers. The placement of helical strakes around the circumference of industrial steel chimneys has been one of the most successful techniques developed. The strakes inhibit the formation of vortices at the very point where they are formed.

Another solution which has been less frequently employed is the perforated shroud. Shrouds inhibit the formation of vortices behind structures due to the continuous "bleeding" of flow through the openings provided.

In Wong's study, a systematic investigation of the resulting loading and wake flow was made for a shroud made up of longitudinally placed slats placed around a cylindrical mast as depicted in the left figure of **Figure 64**. The resultant drag coefficient of various shroud configurations is shown in the right hand figure.

The magnitude of the drag reflects the size of the wake disturbance behind the cylinder. It can be seen that some of the shroud configurations resulted in very significant reductions in drag, and by inference, very significant reductions in the size of the wake disturbance behind the cylinder.

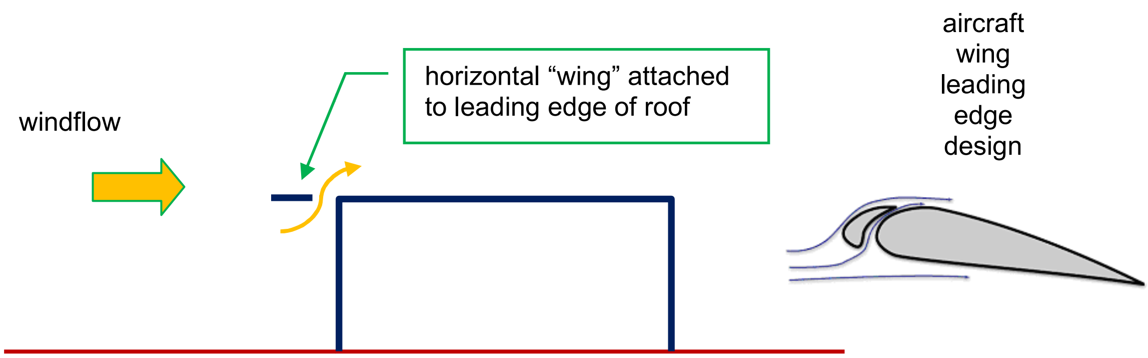
Figure 64 Vortex Suppression Shroud Model



Can the shroud concept be applied to an existing building to lessen its wake impact ?

SLR is aware of at least one case of an aircraft hangar which was potentially prone to very high leading edge suction pressures and where a leading edge "wing" was attached to the building at roof height to reduce the resulting peak pressure loads on the roof. SLR understands that a significant reduction in peak pressure did indeed occur, indicating that the entire wake flow disturbance associated with the flow separation at the leading edge would most likely have lessened as well. The concept idea of such a leading edge wing is shown in **Figure 65**. The concept is aerodynamically identical to the leading edge devices successfully used in aircraft design which aim to achieve the same lessening of wake disturbance (and hence drag) effect.

Figure 65 Leading Edge Wing Concept for Vortex Suppression



The leading edge wing idea is based on sound aerodynamic concepts and would appear to be potentially a cost-effective solution to wake flow mitigation.

11.3 Vortex Suppression - Concept Vane Concept

Reference is made to the following study:

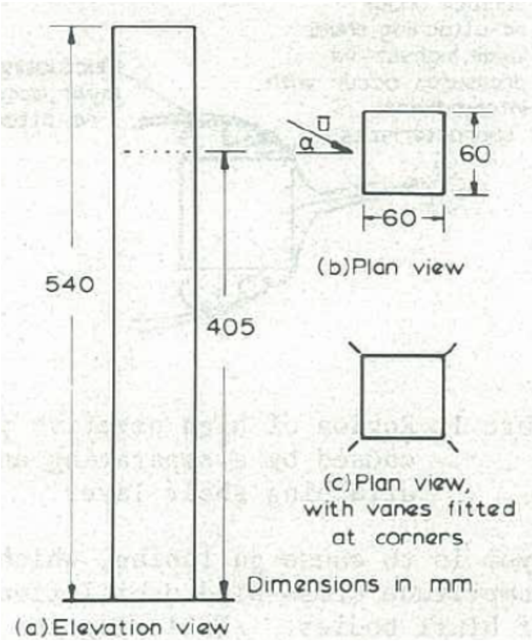
Kwok, K.C.S and Palmer, S.J.
"Pressure Distribution due to Shear Layer Re-Attachment"",
7th Australasian Hydraulics and Fluid Mechanics Conference, Brisbane, 1980.

In this study, prismatic buildings were fitted with vanes at the building corners which had gaps which could vent the flow moving past the building. The purpose of these vanes was to disrupt the separation of windflow at the building corner associated with high localised (negative) pressure and hence higher wake flow disturbance.

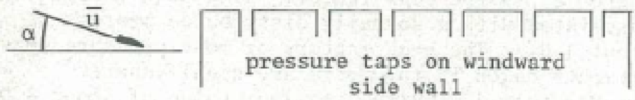
The wind tunnel tests used to carry out this investigation showed substantial reduction in the magnitude of the peak pressures near the corners of these buildings. It is inferred that the wake disturbance behind the buildings would also have decreased.

Figure 66 shows the test building elevation and plan views of the corner vanes with gaps. The table on the right shows the percentage reductions of peak negative pressure at a series of locations along the building wall facing the wind for three oncoming wind angles and two vane sizes. The reductions are significant.

Figure 66 Building Corner "Vane" Suppression Model



Corners fitted with small vanes	$\alpha = 0^o$	-20	9	5	-23	-7	10
	5^o	-12	-25	-22	-17	-6	-13
	10^o	-19	-41	-27	-9	0	0
Corners fitted with small vanes and vents	$\alpha = 0^o$	-22	-5	-2	-2	-3	-2
	5^o	-9	-29	-29	-7	-19	0
	10^o	-13	-34	-27	-17	3	10



The vane concept is aerodynamically similar to the previous option of some form of "leading edge device". Both concepts are designed to disrupt the flow separation taking place on the windward face – the leading edge wing for roof flow separation, the vane concept for side wall flow separation.

Clearly, a quantitative investigation would be required to determine the efficacy of any specific recommended wake flow suppression design – size, gap width, angle of orientation, etc.

Nevertheless, it can be seen that the concept is based on sound aerodynamic reasoning and should in practice be feasible to implement as a building "retro-fit" solution.

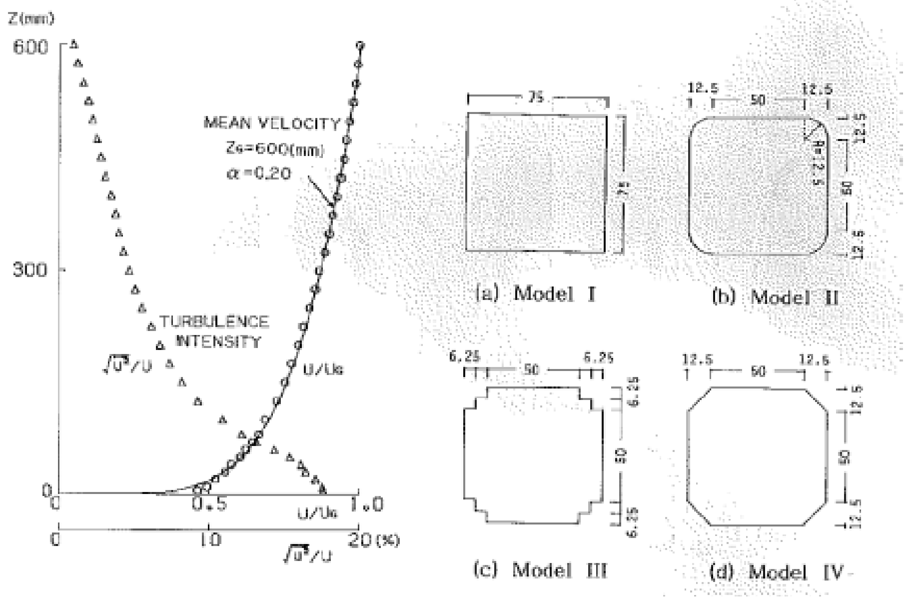
11.4 Alterations to Building Shape, eg Building Corner Details

Reference is made to the following study:

Uematsu, Y., Yamada, M., Higashiyama, H. and Orimo, T.
"Effects of the Corner Shape of High-Rise Buildings on the Pedestrian-Level Wind Environment with Consideration for Mean and Fluctuating Wind Speeds",
JWEIA, 41-44 (1992)

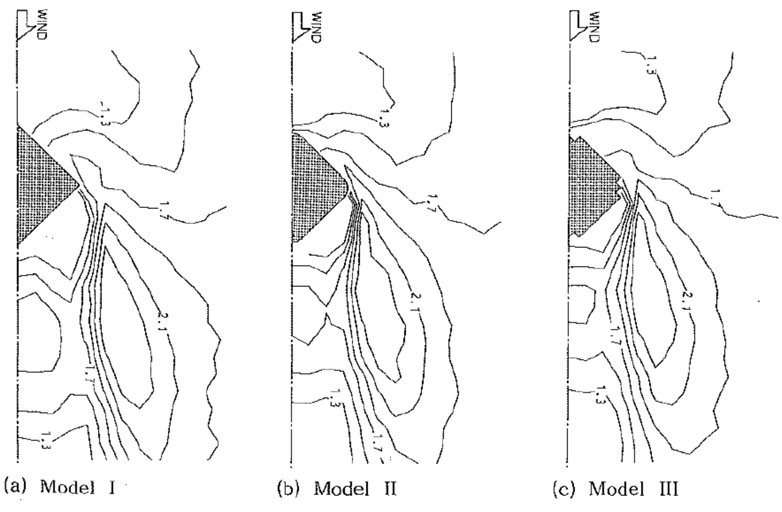
This study involved a series of wind tunnel tests to examine the impact of building corner shape on the resulting ground level (pedestrian) wind environment around the building. The study examined the impact on the so-called "effective" wind speed which took account of both mean and fluctuating wind speeds. The profile used for the tests and the four building corner shapes are shown in **Figure 67**.

Figure 67 Building Corner Shape Study – Wind Profile and Corner Shapes



An example of the output of the study is shown in **Figure 68** for the case of wind impacting on each building at an oblique 45º angle. It can be seen that the area of higher ground level winds (>2.1) is greatest for the sharp-edged building and least for building corner shape **III**.

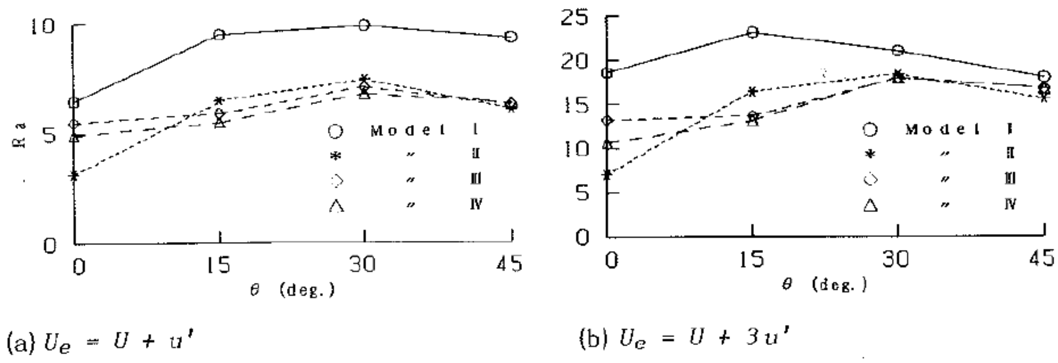
Figure 68 Building Corner Shape Impact Study Sample Results



A summary of the results for oncoming wind angles ranging from 0º to 45º for the four building corner shapes tested is shown in **Figure 69**. The results indicate the extent of area of highest winds, *Ra*, and are shown for two different wind speed metrics: mean plus one standard deviation (left graph) and mean plus three standard deviations (right graph). The latter is representative of very short term gust speeds. The trends are the same in both cases:

- The "rounded" corner shape is best at a wind angle of 0º
- The "square recess cut" and "bevel" corner shape are better at wind angles greater than 0º

Figure 69 Building Corner Study Summary Results



Building corner shape alteration would therefore appear to have potential in terms of lessening the wake impact of a building, although how it might be retro-fitted to an existing building is not immediately clear.

11.5 Roof Attachments

Reference is made to the following study:

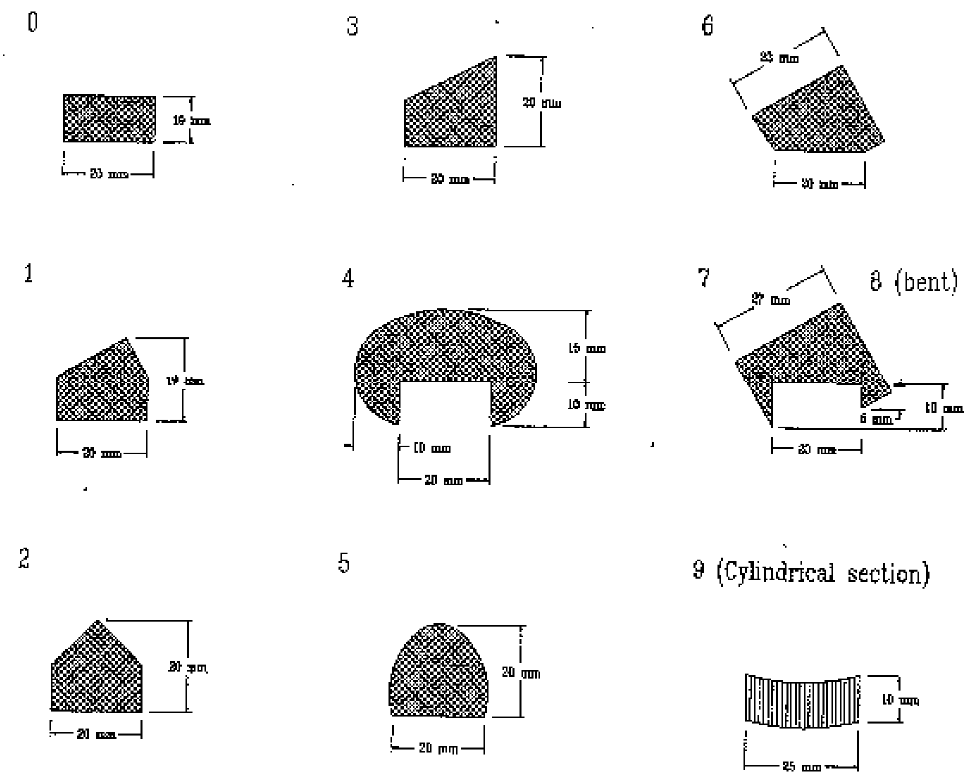
Cochran, L.S., Cermak, J.E. and English, E.C.
"Load Reduction by Modifying the Roof Corner Vortex",
International Conference on Wind Engineereing, New Delhi, January 1995.

This study was the outcome of an ongoing program of wind loading assessment of low-rise buildings at Texas Tech University and damage inspections following the landfall of Hurricane Andrew in Florida in 1992. The specific study investigated the effect that porous screens positioned on the roof of a standard low-rise building had on the associated peak pressure loading on the roof.

This study is of interest because of the relationship between peak roof pressures and salient wake characteristics. For example, it is well known that the far-reaching vortex wake flows which occur with buildings positioned at an oblique angle to the wind are also associated with very high peak pressure near the leading edge of the roof of these buildings.

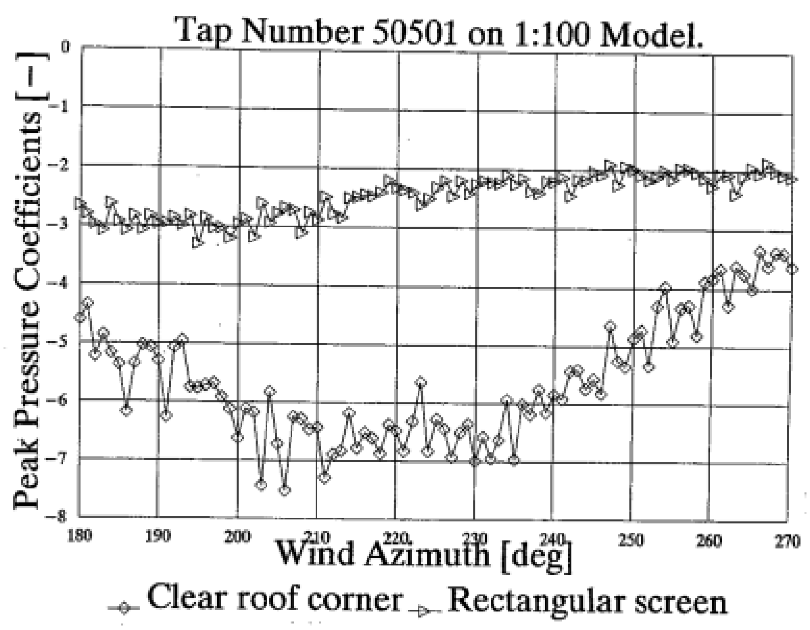
The study investigated a rectangular building (dimension ratios 3:2) with 10 different screens attached near the leading edge of the building roof. The screen shapes are shown in **Figure 70**.

Figure 70 Roof Wind Load Suppression Study Screen Options



An example of the output of the study is shown in **Figure 71** comparing the peak pressures near the leading edge of the roof with NO screen and with a rectangular screen. It can be seen that the rectangular screen reduced the peak pressures by a factor of more than two. The reductions in worst-case wind angle peak (localised) pressure loading for the various screens tested ranged from 19% (screen #0) to 37% (screen #4).

Figure 71 Peak Roof Pressures Sample Output (No screen versus Rectangular Screen)



In addition to reducing the very highest "local" peak pressures (as shown in **Figure 71**), the screens also reduced the overall "area" loads on the section of roof surrounding the screen, indicating that the screens had an impact on an extended area of wake flow surrounding the screen. The reductions in area loading for the various screens tested ranged from 11% (screen #4) to 24% (screen #1).

The above study did not examine the impact of these screens on the associated wake flow at the distances of interest to this study, say up to 20 times the building height downstream. However, it would be expected that both the size of the wake and its accompanying velocity deficits would have been reduced with the addition of the screens.

The roof attachment concept has a similar outcome to the previous "leading edge device" options, ie designed to disrupt the flow separation taking place at the building roof edge facing the wind.

Clearly, a quantitative investigation would be required to determine the efficacy of any specific recommended wake flow suppression design – size, gap width, angle of orientation, etc.

Nevertheless, it can be seen that the concept is based on sound aerodynamic reasoning and should in practice be feasible to implement as a building "retro-fit" solution.

11.6 Flow Relief

The vortex shedding phenomenon is well understood (as shown in the visualisation diagram on the left side of **Figure 72**) and its impact on the wind loading of tall buildings and towers is significant – it is not uncommon in tall, lightweight structures for the cross-wind loads (perpendicular to the wind) caused by vortex shedding to be greater than the along-wind loads (ie in line with the wind). For this reasons, much effort has gone into investigating solutions to minimise this loading. In the case of industrial steel cylinders, it has already been noted that helical strakes are a common form of vortex suppression. An unusual technique which has been successfully used in the design of several tall buildings (eg the Columbia Center tower shown on the right side of **Figure 72**) has been to introduce an opening into the building which enables oncoming windflow to pass directly into the wake behind the building

Figure 72 Vortex Shedding Flow Relief Option

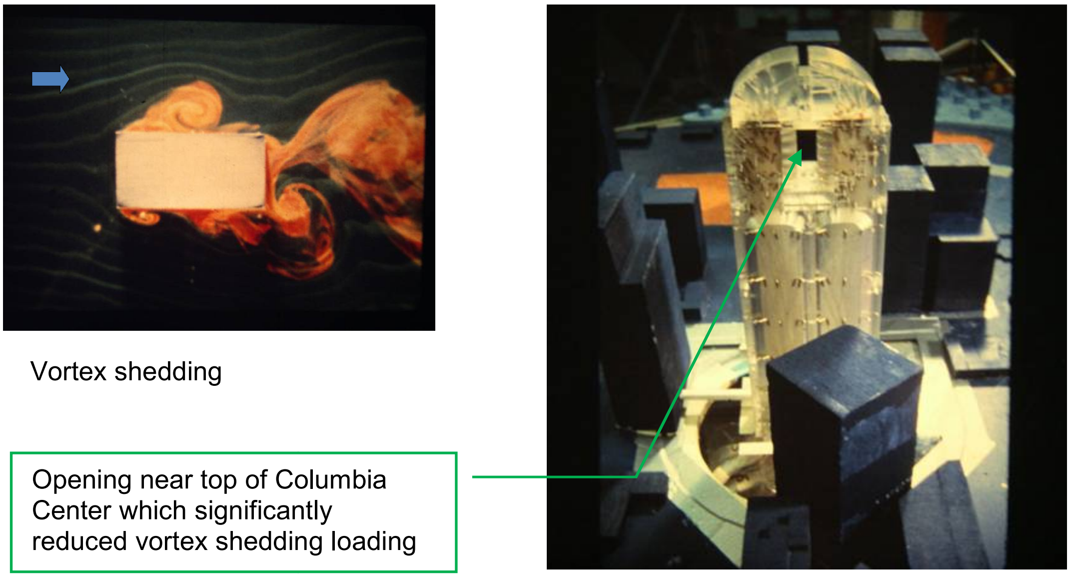
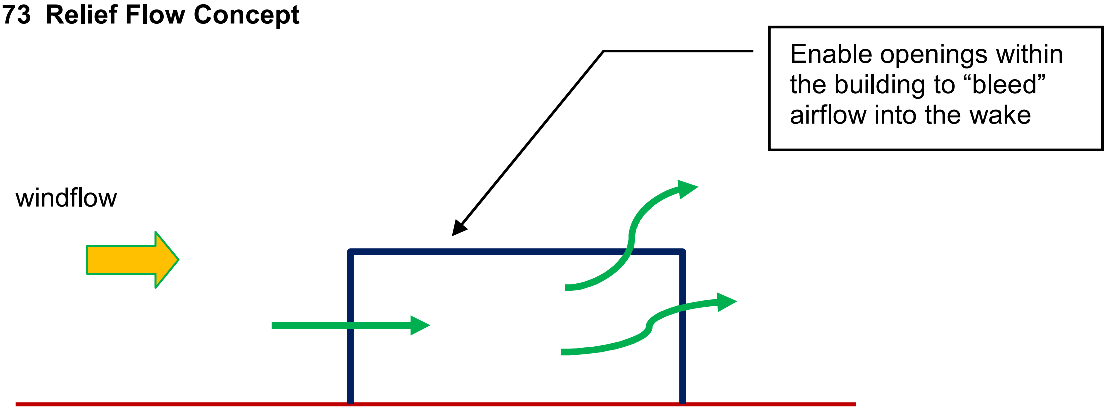


Figure 73 Relief Flow Concept



As in the case of the leading edge devices, the relief flow concept has a sound aerodynamic basis and may, depending upon the usage of the building of concern, be feasible. The idea may not be suitable for commercial buildings but may be feasible for hangars where large slot openings could be located on relevant facades.

11.7 Surrounding “Roughness”

The point was made in **Section 6** that “smooth” flow as encountered over flat, open terrain tends to lead to well delineated wake regions. As the oncoming flow becomes more turbulent due to upstream obstacles, so the wake becomes less well defined.

An option for lessening the wake disturbance behind an existing building could therefore involve adding roughness elements immediately upstream of the development. Such elements (eg trees, other buildings, hoardings such as signage, etc) would however need to be of significant magnitude relative to the building magnitude of concern. A row of shrubs, 1 to 2 m in height, located immediately upstream of a building of height 30 m would have negligible impact on the resulting wake behind the building.

CONCLUSIONS

Guidance Material for Building-Induced Turbulence and Windshear at Airports

Section 12 **Summary and Recommendations**

12 SUMMARY AND RECOMMENDATIONS

12.1 The Current State-of-Art

The Role of Windshear and Turbulence on Aircraft Stability

One of the fundamental characteristics of aircraft stability is the “lift” condition which is responsible for keeping an airplane airborne. At some critical oncoming wind angles, the amount of lift can effectively drop to zero – this condition, termed “stall”, creates a critical stability condition for any airplane. In addition, during the last stages of landing, flare, de-crab and high speed roll take place. In such situations, any **relatively sudden and sustained change** in oncoming windflow condition can present a potential problem to aircraft stability, flight handling and landing performance.

Weather-Related Turbulence and Windshear

It is clear from well-documented experience that weather events such as downbursts or microbursts can create adverse windflow conditions which put aircraft stability at risk.

Building-Induced Turbulence and Windshear

Limited experience exists in relation to adverse aircraft events associated with building-induced turbulence and windshear. However it is clear that the wake flow effects which occur behind buildings are “real” and can reach a magnitude, given the right combination of building-runway proximity and building shape and size, which strongly suggests that guidance needs to be provided for the safe operation of airports.

Available Guidance

Very little guidance currently exists.

- The Australian Airports Association (AAA) has said that the assessment of potential windshear effects on airport operations is essential to the viable operation of airport infrastructure. The AAA’s position is that for proposed developments on-airport, the assessment should be made as a matter of course for any developments within a defined area around runways.
- Amsterdam’s Schiphol Airport uses a **1 in 35** rule (building height to runway distance from building) as an initial acceptance criterion. However, it has been suggested that this could be potentially conservative for buildings of certain shapes and aspect ratios (height to width to depth) which do not produce extensive and hence problematic wake regions of concern.

Similarly, there is virtually no guidance available as to what would constitute an appropriate methodology to carry out such an assessment in relation to building-induced windshear and turbulence.

- For example, the recently updated Application for Development Approval used by Sydney Airport (SACL, May 2010), contains a Note 8 section which requires the proponent of a new development to carry out a Review of Environmental Factors whose Scope of Works must consider **wind shear and turbulence**, OLS intrusion, safety and security, lighting impacts, bird-dust-hazard management, fire management and a T1 MUIP. No guidance however is given as to when a “qualitative” assessment based on best engineering judgement would be adequate in comparison to a more “quantitative” type assessment involving wind tunnel model scale testing or CFD (Computational Fluid Dynamics) simulation.

12.2 Key Outcomes of the Present Study

12.2.1 Key Outcomes of Part A

Section 2 dealt with the sources of windshear and turbulence that can be encountered by aircraft, especially during the crucial take-off and landing stages.

- It was seen that windshear and turbulence can arise from **natural weather phenomenon** (like microbursts), from the **built environment** and in other "man-made" circumstances (eg the **vortex wake flow** behind jet aircraft)
- In terms of building-induced wake effects, some initial descriptions of wake flow, vortex shedding and the variations in location and time induced by the variations of oncoming windflow provided an early indication that building wakes can take complex form depending upon the shape, dimension and orientation of the building concerned.

Section 3 dealt with the issue of aviation windshear risk and provided case studies primarily related to weather-induced windshear.

- This class of windshear event led to the development of sophisticated wind monitoring systems deployed around airports which in turn led to an understanding of the magnitude of windshear likely to cause flight difficulties, especially during take-off and landing.

Section 4 provided case studies involving building-induced windshear (and turbulence), including Australian case studies (at Canberra Airport).

- The circumstances under which building-induced windshear (and turbulence) arise suggest that building-induced windshear events of concern would arise less frequently than weather-induced events (eg from microbursts, gust fronts, etc).
- However, it is likely that the frequency of building-induced windshear events will rise in coming years, in response to (a) the ever-growing pressure on airport operators around the world to maximise the value of the seemingly large areas of available land on their premises and (b) increased air traffic and the move towards larger aircraft utilisation (which have the perception of being able to cope with more difficult windflow circumstances) leading to an increase in the likelihood of aircraft using runways under strong crosswind conditions.

Section 5 provided a summary of world-wide response to building-induced windshear in terms of regulation and guidance material. This has taken primarily two forms.

- "Management" Tools: in Australia, this may be in the form of aerodrome information contained in an ERSA guidance note (eg Canberra Airport has one for Runway 35). In the UK, this may be in the form of an AIP guidance note (eg London's Heathrow Airport has one for Runway 27R and Runway 27L).
- Positional "Rules": An example is the 1:35 rule which arose from the detailed studies of building-induced windshear undertaken at Amsterdam's Schiphol Airport

12.2.2 Key Outcomes of Part B

Section 6 included a detailed exposition of quantitative studies (involving wind tunnel testing and/or CFD) describing the extent of the wake disturbance behind primarily regular building shapes (ie rectangular, sharp-edged buildings).

- The wake disturbance behind bluff bodies (ie buildings) impacts both the mean speeds and turbulence of the oncoming windflow.
- The most readily identifiable feature of the wake is the low-speed "cavity" region of re-circulating flow immediately behind the building. This typically extends up to around 5 times the building height.

- Wake effects however (both in terms of mean wind speed deficit and increased turbulence) extend well past the recirculation zone, in some cases (depending upon building orientation) to beyond 20 times the building height.
- The extent of the wake (ie the region of disturbance to the upstream flow) – in terms of its physical dimension and the magnitude of the disturbance contained therein – will depend upon building shape (eg square, rectangular, etc), building orientation (ie building facades perpendicular to the wind, facades at 45º to the wind, etc), aspect ratio (height to building width ratio) and surrounding terrain conditions (open country terrain, suburban terrain, etc.
- A particular case of interest is when certain building shapes are oriented at an oblique angle to the approaching windflow. In this case, a pronounced "delta" vortex forms at the leading corner of the building which persists for many building dimensions downstream. Tests indicate that increased turbulence levels exist well beyond the point where the mean wind is restored to its upstream (unaffected) level.
- **Section 6** showed that a **simple "*one-size-fits-all*" rule** for determining the magnitude of wake disturbance (for both mean winds and turbulence levels) **based just on building height**, and accurate for any building shape and any combination of building dimensions and building orientation, **is not apparent**. For example, two rectangular buildings with exactly the same ratios of width-depth-height but of different actual scale (eg one twice as big as the other) result in different wake impacts relative to their heights.
- If it was desired to determine the extent of building wake effects using a simple *"one-size-fits-all"* prediction rule based for example on the number of building heights downstream, such a rule would have the potential to end up being **highly conservative** if it was required to cover a reasonable range of building shapes, dimensions and orientation.
- **Section 6** established some useful benchmark values for building-induced wake effects for rectangular buildings in upstream open terrain conditions and for the case of no flow re-attachment (ie building width perpendicular to the flow greater than building length in line with the flow).
- A reasonable estimate for the **potential maximum magnitude of horizontal windshear** (of the mean wind) experienced by an object moving across a building wake (close to the ground) is simply the **magnitude of the mean wind speed at top of building height in the approach flow**. Important considerations follow on from this observation.
- The potential maximum magnitude of horizontal windshear (of the mean wind) experienced by an object moving across a building wake will **increase with building height**.
- The potential magnitude of horizontal windshear (of the mean wind) experienced by an object moving across a building wake will be highest if the terrain conditions upstream of the building are "smooth", ie "open" flat terrain.
- **Table 5** of **Section 6.8** provides a set of estimates which can be used to determine the magnitude of mean crosswind deficit of an object moving across the wake behind a building, for the case of a rectangular building, height between 30 m to 40 m, no re-attachment, open country terrain.
- The **Table 5** estimates are given as a ratio of upstream mean wind speed, V_H (at building height, H). This then provides a direct link with which to establish the likelihood or frequency of occurrence of wake-induced horizontal windshear events of a given magnitude. This frequency of occurrence can be readily determined by calculating the frequency of occurrence of the mean wind speed at the height of the top of the building of concern, taking into account the surrounding terrain and the optimal directionality which has the potential to produce wakes interacting with airport operations.

Section 7 included a detailed examination of the three primary tools available for determining the extent of the wake disturbance behind buildings:

- Qualitative - "Desktop", "Expert Opinion"
- Wind Tunnel Testing (Quantitative) - Using Scaled Models of the Building and Wind
  - ✓ SAND SCOUR, SAND EROSION, OIL STREAKLINE
  - ✓ DISCRETE SENSOR - using either IRWIN or HOT-WIRE SENSORS
  - ✓ PARTICLE IMAGING VELOCIMETRY (PIV)
- CFD Modelling (Quantitative) - 3-D Computer Simulation

Some explanation was provided as to the reasons why **qualitative studies** (based on the best engineering judgement of wind engineers) can lead to **variable** and **sometimes unconservative estimates** of the potential extent of downstream building wake influence.

It is equally clear that the **wind tunnel and CFD options** provide **reliable and quantitative outputs** in terms of the extent of building wake disturbance (for both mean winds and turbulence levels).

Section 8 provided three examples of quantitative studies of building wake assessment using the wind tunnel and CFD illustrating the usefulness of such techniques in establishing reliable estimates of the extent of the wake disturbance behind buildings (of any shape).

12.2.3 Key Outcomes of Part C

Section 9 described the aviation regulatory framework in Australia and the degree to which on-airport building developments are controlled via OLS rules.

Section 10 provided a risk-based approach to the control of on-airport building developments dependent primarily upon building shape, dimension and orientation.

- It was firstly noted that a simple "one-size-fits-all" building height multiplier rule for assessing the acceptability or otherwise of building projects would have obvious cost and timing advantages, by obviating the need for detailed wind assessments.
- Examples of such rules are the Schiphol 1:35 rule or SACL's suggested 1:10 rule - where the ratio is taken to be the height of the building of interest compared to the distance from the runway centreline.
- On the basis of the building wake characteristics examined in this study and aviation incident reports, it is likely that such a rule would have to be highly conservative to capture a reasonable range of potential building shapes and configurations.
- While easy to apply, such a conservative rule would probably exclude a large number of developments which, under proper detailed assessment, might have easily passed the acceptance criteria adopted for the project.
- **Section 10** therefore provides a three-step process involving both qualitative and quantitative methodologies depending upon building shape, dimension and orientation, with the qualitative option guided by the **Section 6** data for simple rectangular building shapes and the quantitative options leading to a choice of either wind tunnel testing or CFD modelling.

12.2.4 Key Outcomes of Part D

Section 11 provided options for mitigating building generated turbulence and windshear for existing structures where safety risks are identified.

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	No 03/03	Airbus A321-200, F-GTAA
	No 08/05	DHC-8-311 Dash 8, G-JEDE
	No 12/08	Reims Cessna F172M Skyhawk, G-BFPM

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"Automated Microburst Wind-Shear Prediction"

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"Numerical simulation to Determine the Effects of Incident Wind Shear and Turbulence Level on the Flow Around a Building",
JWEIA, 46&47 (1993)

AVIATION SAFETY AND WINDSHEAR – A HISTORICAL PERSPECTIVE

It is instructive to examine a selection of the numerous world-wide studies documenting aviation accidents/incidents where windshear was deemed to have played a dominant role. These indicate the frequency and magnitude of windshear conditions of concern to aviation safety so that the sub-set issue of building-induced windshear (and turbulence) can be put into context.

B.1 Key Studies of Relevance to Windshear

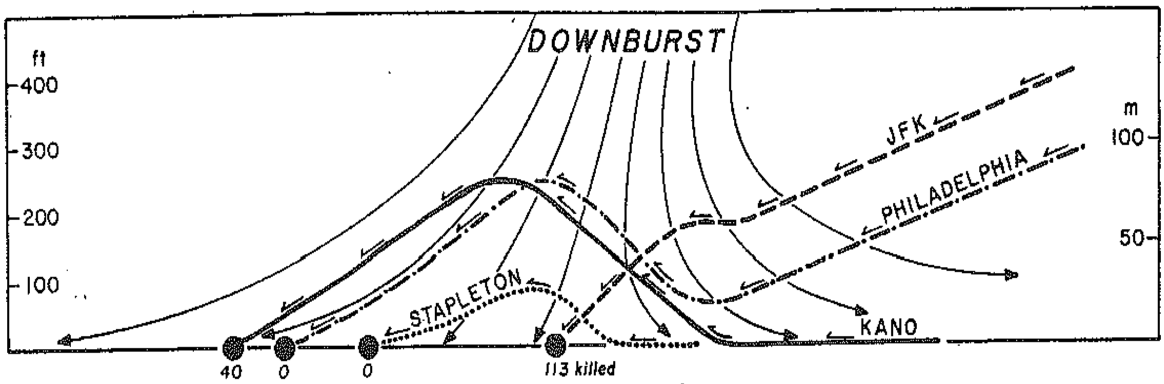
Ref: T. Theodore Fujita (1978)
"Thunderstorm Downbursts – An Important Structural and Aviation Hazard".

Important foundation work was carried out by Fujita (and his colleagues at IIT) in relation to microbursts and other convective storm activity. Fujita's studies were seminal in identifying the role played by such weather systems in aviation accidents. Prior to this, the most common cause ascribed to such events was "*pilot error in severe weather*". It then became understood that these events had often involved the unintentional penetration of aircraft at low levels into windshear-related activity. The first four such microburst-related incidents identified as such were:

BOAC	takeoff	Kano, Nigeria	24 June 1956
Eastern Airlines	landing	JFK, New York	24 June 1974
Continental Airlines	takeoff	Stapleton, Denver	7 August 1975
Allegheny	landing	Philadelphia	23 June 1976

Each of the above aircraft encountered difficulties which ultimately led to a crash landing (and 153 fatalities in total) as they either landed or were taking off (refer **Figure B1**) within the most intense affected area of a microburst.

Figure B1 Composite Flight Paths (Vertical Cross-Section) of Four Aircraft Microburst Events



Ref: Skeen & Reed (2004)
"Weather-Related Aviation Accident Investigations at the National Transportation Safety Board".

This paper describes the role of the National Transport Safety Board (NTSB) in investigating civil aviation accidents in the United States, determining probable cause and issuing safety recommendations aimed at preventing future accidents. Since 1967, the Safety Board has investigated more than 12,000 aviation accidents and issued more than 5,000 aviation-related safety recommendations. The Safety Board now includes meteorologists who assist in weather-related safety studies and provide weather-related instruction and training to Safety Board staff and other accident investigators. Safety recommendations are the most important product of the Safety Board.

AVIATION SAFETY AND WINDSHEAR – A HISTORICAL PERSPECTIVE

The NTSB database of Safety Recommendations from 1967 to 2004 contains 249 weather-related recommendations, with the following breakdown by weather phenomenon type:

Fog	1%
Turbulence	**12%**
Thunderstorm & Windshear	**23%**
Icing	50%
Other	15%

The above breakdown provides some context in terms of the relative proportion of weather-related issues contributing to aviation situations of concern.

Ref: Wolfson, Delanoy, Forman, Hallowell, Pawlak and Smith (1994) "Automated Microburst Wind-Shear Prediction".

While devoted primarily to the issue of predicting windshear conditions, this study lists 21 aircraft incidents documented in US NTSB (National Transportation Safety Board) publications in the period 1975 to 1994 ascribed to thunderstorm outflow or microburst windshear involving 438 fatalities. This listing is reproduced in **Table B1**.

Table B1 Listing from Reference Wolfson et al (1994) of Microburst-Related Aircraft Accidents

Table 1. Aircraft Accidents in the United States Attributed to Thunderstorm Outflow or Microburst Wind Shear in the Past Twenty Years (1975–1994)

Date	*Location*	*Aircraft*	*Fatalities*	*Injuries*	*Uninjured*
24 June 1975	Jamaica, NY	Boeing 727	112	12	0
7 Aug. 1975	Denver, CO	Boeing 727	0	15	119
23 June 1976	Philadelphia, PA	McDonnell-Douglas DC-9	0	86	20
3 June 1977	Tucson, AZ	Boeing 727	0	0	91
21 May 1982	Dayton, OH	BAC 1-11	0	0	48
9 July 1982	New Orleans, LA	Boeing 727	153	9	7
28 July 1982	Flushing, NY	Boeing 727	0	0	129
31 May 1984	Denver, CO	Boeing 727	0	0	105
13 June 1984	Detroit, MI	McDonnell-Douglas DC-9	0	10	46
2 Aug. 1985	Dallas/Ft. Worth, TX	Lockheed L-1011	135	28	2
11 July 1987	Washington, DC	Boeing 727	0	0	87
15 Sept. 1987	Tulsa, OK	Boeing 727	0	0	62
3 Nov. 1987	Orlando, FL	Lear Jet 35A	0	0	5
1 June 1988	Jamaica, NY	Boeing 747	0	0	157
26 Apr. 1989	Mt. Zion, IL	Cessna 208A	0	1	0
22 Nov. 1989	Beaumont, TX	Saab-Fairchild 340A	0	0	37
18 Feb. 1991	Thornton, TX	Cessna 172N	1	0	0
14 Feb. 1992	Lanai, HI	Beech D-18H	0	0	1
7 Jan. 1993	Akutan, AK	Grumman G-21A	0	0	8
26 Apr. 1993	Denver, CO	McDonnell-Douglas DC-9	0	0	90
2 July 1994	Charlotte, NC	McDonnell-Douglas DC-9	37	20	0

AVIATION SAFETY AND WINDSHEAR – A HISTORICAL PERSPECTIVE

Ref: Perry & Symons (1994)
"The Wind Hazard in Great Britain and its Effects on Road and Air Transport".

This paper presented a review of wind hazards in Great Britain and the associated impact on road and air transport and included a detailed analysis of aviation accidents for the 1987-1992 period. The source data were individual incident reports documented in UK Air Accident Branch (AAIB) Bulletins from May 1987 to December 1992.

Weather was judged to have been a major causal factor in about 16.6% (255 out of 1535 accidents) of the accidents examined (17.3% for aeroplanes and 11% for helicopters).

This figure compared well to the figures for weather-related accidents in two previous studies carried out by the UK's General Aviation Committee published (using data obtained in the period 1967 to 1976) and another study of AAIB Bulletins by W.S. Pike (for the period 1977 to 1986).

Perry and Symons' study also included an analysis of the main types of weather contributing to the documented accidents – wind, low cloud, icing and "other" - and found that wind was a major factor in approximately 60% of the accidents examined.

B.2 ICAO "Manual on Low Level Wind Shear and Turbulence"

Provisions for international civil aviation are adopted by the International Civil Aviation Organization (ICAO) - a body of the United Nations with its headquarters in Montréal. These provisions are located in 18 annexes; Annex 3 describes the meteorological service for international air navigation and corresponding international standards and recommended practices.

One topic, windshear warnings (section 7.4), references the ICAO's Manual on Low-level Wind Shear and Turbulence (Ref 9817) as a guide on the subject of windshear. This replaced the previous guidance document, Circular on Wind Shear, published in 1987.

Ref: ICAO, 2005:
"Manual on Low-Level Wind Shear and Turbulence".

On page iii (par 1) of the Manual – sub-section titled Worldwide Windshear Accidents – can be found the following extract:

> *From 1964-1983, low-level (ie below 1,600 ft altitude) windshear was cited in at least 28 large transport aircraft accidents/incidents that together resulted in over 500 fatalities and 200 injuries.*

In recent committee meetings devoted to a review of the Manual, it was noted that windshear-related accidents have continued post-1983 and that more comprehensive references to windshear exist, including documentation published by the Aviation Safety Network (an exclusive service of the Flight Safety Foundation) where it is stated that:

> *The total number of commercial wind shear / downdraught accident deaths since 1943 is 1438 (noting that this is not just large transport aircraft).*

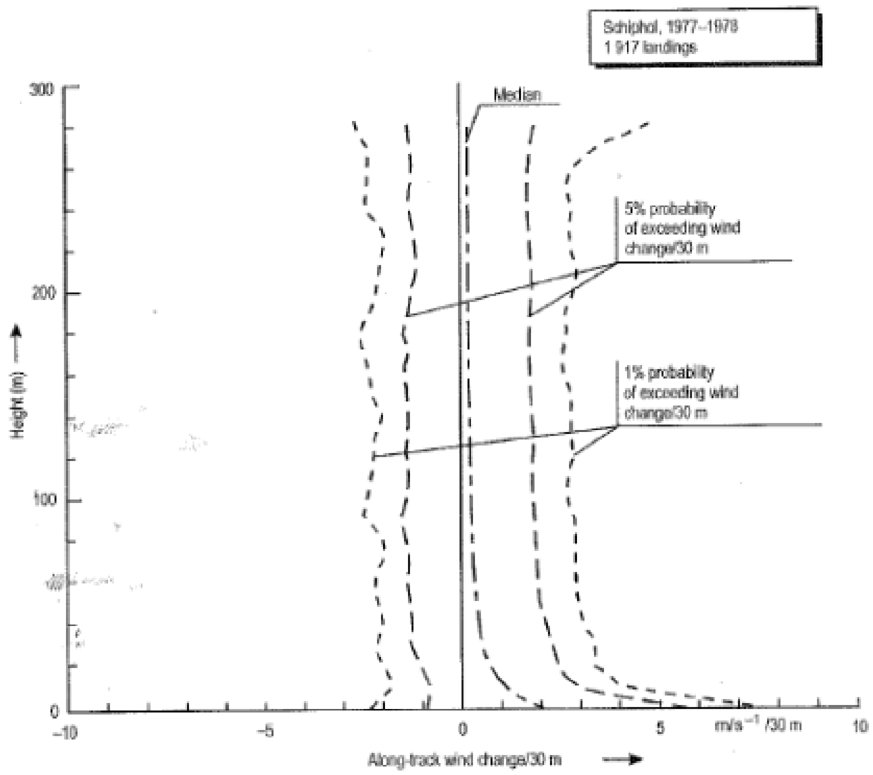
Chapter 3 of the Manual provides a comprehensive description of the various meteorological conditions and other circumstances causing low-level windshear, including windflow around obstacles (refer *Section 3.2* of the Manual). *Sub-section 3.2.2* specifically mentions windshear caused by large buildings located near runways.

Section 3.7 contains valuable data providing an indication of the statistics of low-level windshear in the vicinity of aerodromes, including a study involving 10,000 landings by KLM B747s and over 9,000 landings by BA B474s.

AVIATION SAFETY AND WINDSHEAR – A HISTORICAL PERSPECTIVE

Figure B2 taken from this dataset shows probabilities of exceeding given windshear values, all of which are applicable to Schiphol Airport – of specific interest to the present SLR study.

Figure B2 Exceedance Probabilities for Along-Track Wind Change/30m per Landing



B.3 Response to the Windshear Risk to Aviation Safety

The growing awareness of the risks posed by windshear phenomena to aviation safety (especially in the US) led to the development in the 1970's of airport detection systems termed Low Level Windshear Alert Systems (LLWAS).

These systems involved the use of as many as 30 anemometers situated around an airport to detect potential windshear conditions. Through correlation studies (eg with pilot reports of windshear) and confidence trials aimed at maximising the detection success rate and minimising false positives, Air Traffic Controllers began to be able to use anemometer array data to convey LLWAS alerts to pilots during predicted critical times.

The very first LLWAS system (LLWAS 1) was developed by the Federal Aviation Administration (FAA) in 1976 in response to the 1975 Eastern Air Lines Flight 66 windshear accident in New York. LLWAS 1 was then deployed at over 100 FAA towered airports between 1977 and 1987 and at other airports around the world.

The next generation LLWAS 2 deployment (1988-1991) included software and hardware upgrades to improve windshear detection algorithms.

AVIATION SAFETY AND WINDSHEAR – A HISTORICAL PERSPECTIVE

A second upgrade program of interest to this study began in 1994, following the USAir Flight 1016 accident at Charlotte, NC, which occurred in that year. It was determined that the LLWAS methodology was being compromised due to **increased obstructions around airport LLWAS wind sensors arising from the construction of new buildings**. In other words, LLWAS wind sensors around airports were being increasingly impacted by building-induced windflow disturbance generated by the local built environment.

Since that time, the Federal Aviation Administration (FAA) began deploying two new wind shear detection systems: the Terminal Doppler Weather Radar (TDWR) and the third-generation Low Level Windshear Alert System (LLWAS 3). These are discussed in greater detail in subsequent sections of this report.

B.4 The Australian Experience

Ref: Potts
"Low Altitude Windshear at Major Australian Airports and the Risks to Aviation".

This paper recognised the potential impact of low altitude windshear on aircraft during landing and takeoff and the particular significance of convective storm activity such as gust fronts and microbursts. It was also observed that few aircraft incidents had been attributed to such events in Australia.

The possible causes for this paucity of reported weather-related incidents suggested by Potts were:

- These events are typically small scale and only affect the approach/departure flight corridor for a short period of time;
- Observing the windshear associated with gust fronts and microbursts requires an appropriate network of anemometers and/or a suitably configured Doppler radar (or equivalent) and because there has been a lack of such systems in Australia historically, past incidents could have simply been missed;
- The typical traffic density across many Australian airports has been relatively low; and
- Air traffic control policies have been conservative.

Potts suggested that, as a result, the perceived level of risk associated with low level windshear by the aviation industry (in Australia) has been low, although several recent incidents attributed to windshear imply an increased awareness of the significance of the associated risks.

The following historical studies looking at the incidence of windshear and the potential risks to aviation were noted:

- Anderson and Clark (1981) - who surveyed a large number of military and civilian pilots on experiences with windshear;
- Spillane and Lourenz (1986) - who assessed the incidence of windshear at Sydney Airport using single station anemograph data; and
- Grace and Hancy (1988) - who reported on a 'dry' microburst observed by a glider pilot in South Australia.

AVIATION SAFETY AND WINDSHEAR – A HISTORICAL PERSPECTIVE

B.4 Australian Case Studies

Ref: Mills and Pendlebury (2003)
"Processes Leading to a Severe Wind-Shear Incident at Hobart Airport".

Case 1 Hobart Airport 21/01/1997 Qantas Flight QF617

On 21 January 1997, Qantas flight QF617 encountered extreme turbulence at approximately 500 ft altitude as it approached Hobart Airport. A near-surface southerly wind surge under-cutting a strong synoptic-scale northwesterly airflow generated a vertical windshear (of the horizontal wind) of over 30 knots over a depth of around 25 m.

Post-analysis showed that a combination of heating over land during daylight hours, leading to locally lowered pressures, and the rapid movement of a mesoscale high-pressure system around the southern coast of Tasmania led to a local intensification of the onshore pressure gradient and the rapid development of a flow-reversal in the lowest levels south of Hobart Airport.

While the weather patterns which caused this event might be expected to occur relatively routinely over southern Tasmania in summer, an analysis of archived radiosonde data suggests that this event was unusual in its intensity.

Ref: Potts
"Low Altitude Windshear at Major Australian Airports and the Risks to Aviation".

Case 2 Perth Airport, Runway 24 02/09/1999 0428 hrs Boeing 747

As the Boeing 747 was landing and immediately prior to touchdown, the aircraft experienced a sharp roll to the right of around 8 degrees followed by a similar sharp roll to the left, the latter causing the outer left engine pod to strike the ground. There was no other damage.

At the time of the accident Perth was under the influence of strong to gale force west-northwest airflow caused by a complex low pressure system situated to the south of Western Australia. A series of fast moving cold fronts were embedded in the airstream accompanied by scattered showers and isolated thunderstorms. Radar data for the period showed that a line of showers passed across Perth Airport around 0412 hours and moved quickly to the east at a speed of around 20 m/s to 25 m/s. Bureau of Meteorology (BoM) wind records obtained from the BoM anemometer located approximately 1200 m west of the runway 24 threshold showed that the wind direction backed more westerly and the wind speed increased sharply. The wind speed then eased gradually and by 0426 hours the mean wind was a westerly of 7 m/s gusting to 9 m/s. A heavy shower then moved across the airport and the mean wind speed increased sharply to 12 m/s with gusts to 18 m/s. This occurred just as the aircraft was landing.

The aircraft's roll response is consistent with a sudden increase in crosswind component from the right, and likely presence of increased turbulence that would have been associated with the frontal change as it moved across the airport.

AVIATION SAFETY AND WINDSHEAR – A HISTORICAL PERSPECTIVE

Case 3 Brisbane Airport, Runway 19 17/01/2001 2129 hrs Boeing 737

At approximately 2129 UTC, 17 January 2001, a Boeing 737 aircraft was approaching runway 19 at Brisbane Airport and aborted at an altitude of around 60 m when heavy rain and hail was encountered. The direction of flight was maintained, the power was increased to go-round thrust and the aircraft began to climb. Soon after initiating the climb-out the airspeed rapidly decreased, the nose pitched down several degrees and the rate of climb decreased markedly. Although the power was increased to maximum thrust at this time the aircraft remained at around 300 m for approximately 17 seconds before climbing rapidly. The aircraft then landed after a second approach.

Weather radar data at the time showed an intense multi-cellular storm near Brisbane Airport which was moving northeast at a speed of approximately 17 m/s. The radar also showed evidence of the new core development on the northern flank of the leading cell right in the vicinity of the runway 19.

The BoM anemometer on Brisbane Airport is located close to the threshold of runway 19. During the passage of the above storm cells, there was a rapid increase and then decrease in wind speed, the temperature dropped by 1.5ºC and a significant change in wind direction from southeast to south and then west. Flight recorder data showed that the winds encountered by the aircraft were consistent with the changes occurring at the BoM anemometer site both in relation to wind speed and wind direction, supporting the incidence of an asymmetric microburst associated with the development of the new storm cell.

The Perth and Sydney windshear-related incidents led to the BoM increasing its wind monitoring surveillance at key airports (including a Doppler radar installed at Sydney in 1999) to support future safety investigations and studies on the level of risk associated with windshear.

Ref: Potts, Hanstrum & Dunda
"Sydney Airport Wind Shear Encounter – 15 April 2007".

Case 4 Sydney Airport, Runway 16R 15/04/2007 0923 hrs Boeing 747

At approximately 0923 hours on 15 April 2007, a Boeing 747 encountered windshear while attempting to land towards the south on runway 16R at Sydney Airport (located on the east coast of Australia). The aircraft was at about 100 ft AGL when there was a rapid loss of airspeed and the pilot reported a sensation of being pushed down and sideways. At that time the pilot initiated a windshear escape manoeuvre as the enhanced ground proximity warning system (EGPWS) sounded a windshear alert.

The aircraft touched down heavily with a maximum vertical acceleration recorded at 2.34 g causing the dislodgement of a number of ceiling panels. Three seconds after the initial touchdown the aircraft touched down firmly again and then climbed to go-round and make a successful landing several minutes later. This incident is of particular interest as it led to a study to investigate technology options for a windshear alert system at Sydney Airport.

Flight Data Recorder covered altitude, wind speed and wind direction during the 3-minute period when the aircraft approached runway 16R, touched down and then climbed after aborting the landing. Initially, the aircraft experienced northwest winds around 10 knots shifting to the northeast below 1400 ft and increasing to 15 knots as it encountered the expected sea breeze. At 800 ft, the wind shifted from northeast to south-southwest and increased to around 20 knots, consistent with the aircraft descending through the upper boundary of the gust front that had passed across the airport earlier. When the aircraft was at 100 ft and 0.6 km from the runway threshold the wind rapidly shifted from 190º/18 knots to 280º/12 knots and the aircraft recorded an airspeed loss of 28 knots in a period of 7 seconds. The pilot initiated a go-round at this time with the aircraft touching down heavily before climbing. As the aircraft climbed the observed wind was consistent with the presence of the divergent outflow.

The Kurnell Doppler radar clearly identified and confirmed the suspected microburst activity which coincided in both timing and locale with the above incident.

AVIATION SAFETY AND WINDSHEAR – A HISTORICAL PERSPECTIVE

B.5 UK Case Studies

Ref: UK AAIB Bulletins

The reader is referred to the detailed analysis of aviation accidents/incidents documented in UK Air Accident Branch (AAIB) Bulletins. Numerous windshear-related accidents have been documented within these AAIB Bulletins.

The reports provide useful information as to the severity of windshear which apparently affected the performance of the aircraft of interest so significantly that it challenges the compensation capabilities of the pilot and the aircraft.

AUSTRALIA'S REGULATORY FRAMEWORK IN RELATION TO RESTRICTIONS ON SITING OF AIRPORT BUILDINGS

In this section, the regulatory framework covering aviation safety in Australia is briefly described so that subsequent recommendations made in this report dealing with building-induced windshear can be put into context.

C.1 CAA, CASA, MOS, CASR, AC, AIP, ERSA, OLS

CASA (the **Civil Aviation Safety Authority**):

- Is responsible under section 9(1)(c) of the **Civil Aviation Act 1988** (the Act) for developing and promulgating appropriate, clear and concise aviation safety standards.
- Is also responsible under section 9(2)(b) and section 16 of the Act for promoting full and effective consultation and communication with all interested parties on aviation safety issues, and must, in performing its functions and exercising its powers, where appropriate, consult with government, commercial, industrial, consumer and other relevant bodies and organisations.

Civil Aviation Safety Regulations (CASRs) and the **Manual of Standards (MOS)** are the means **CASA** uses in meeting its responsibilities under the Act for promulgating aviation safety standards.

- **CASRs** establish the regulatory framework (Regulations) within which all service providers must operate.
- The **MOS** comprises detailed technical material and specifications (Standards) prescribed by **CASA**, of uniform application, determined to be necessary for the safety of air navigation.
- In the circumstance of any perceived disparity of meaning between **CASRs** and the **MOS**, primacy of intent rests with the regulations.
- Of particular interest to the present study is **MOS Part 139 – Aerodromes (Ver 1.4, April 2008)**. The responsibility for the technical matters within **MOS Part 139** lies with the **Aviation Safety Standards Division**.
- The other mechanism used by **CASA** to meet its responsibilities under the Act is via **Advisory Circulars (ACs)**. **ACs** are intended to provide recommendations and guidance to illustrate a means, but not necessarily the only means of complying with the Regulations. **ACs** may explain certain regulatory requirements by providing interpretive and explanatory materials.

Service providers (such as aerodrome operators) must document internal actions (Rules) in their own operational manuals, to ensure the maintenance of and compliance with standards and to put into effect those, or similarly adequate, practices.

C.2 Responsibilities of an Aerodrome Operator

In order to be able to operate an aerodrome, an operator must have prepared and submitted (to **CASA**) an **Aerodrome Manual** in accordance with the requirements set out in MOS Part 139 and updated in accordance with the governing regulations. The standards to meet the requirements are set out in various chapters in the **MOS**. **CASA** retains one copy of the **Aerodrome Manual**. The aerodrome operator keeps their copy of the **Aerodrome Manual** at the aerodrome or at the operator's principal place of business and available for **CASA** audit purposes.

Certain information relating to aerodrome operations is required to be published in an **Aeronautical Information Publication (AIP)**. Such information must be included in the operator's **Aerodrome Manual** and can be published in

- **AIP - Enroute Supplement Australia (ERSA)**,
- **AIP - Runway Distances Supplement (RDS)**, and
- **AIP - Departure and Approach Procedures charts (DAP).**

C.3 Management of Obstacles at Aerodromes

A topic of particular interest to this study is the means by which the airspace around an aerodrome is controlled in order to guarantee aviation safety and the accompanying restrictions placed on "**obstacles**" within that space. The standards governing the management of obstacles around aerodromes are found in **MOS Part 139, Section 7**.

In MOS 139 Section 7.1.1.2, an **obstacle** is defined as any object that:

- stands on, or stands above, the specified surface of an **obstacle restriction area** which comprises the runway strips, runway end safety areas (RESAs), clearways and taxiway strips; and
- penetrates the **Obstacle Limitation Surfaces (OLS)**, a series of surfaces that set the height limits of objects, around an aerodrome.

MOS 139 Section 7.1.2.states that "objects", except for approved visual and navigational aids, must not be located within the obstacle restriction area of the aerodrome without the specific approval of **CASA**.

C.4 General Guidance Regarding Obstacle Management

The following key points are extracted from MOS Part 139 Section 7.1:

An aerodrome operator must monitor the **OLS** applicable to the aerodrome and report to CASA any infringement or potential infringement of the **OLS**.

Aerodrome operators need to liaise with appropriate planning authorities and companies that erect significant structures to determine potential infringements.

Whenever a new obstacle is detected, the aerodrome operator must ensure that the information is passed on to pilots, through **NOTAM**, in accordance with the standards for aerodrome reporting procedures set out in MOS Part 139 / Sec10.

Under Part 139 any object which extends to a height of 110 m or more above local ground level must be notified to **CASA** and any object that extends to a height of 150 m or more above local ground level must be regarded as an obstacle unless it is assessed by CASA to be otherwise.

Under Part 129, Section 7.1.6.1, if a proposed object or structure is determined to be an obstacle, details of the proposal must be referred to **CASA** the Authority to determine whether it will be a hazard to aircraft operations.

Under Part 129, Section 7.1.6.4, **temporary or transient (mobile) obstacles**, such as road vehicles, rail carriages or ships, in close proximity to the aerodrome and which penetrate the **OLS** for a short duration, must be referred to **CASA** to determine whether they will be a hazard to aircraft operations.

Under Part 129, Section 7.1.6.5, a **fence or levee bank** that penetrates the **OLS** must be treated as an obstacle.

C.5 Critical Aerodrome Dimensions Relevant to the OLS

Australia has adopted the ICAO's methodology of using a code system – the Aerodrome Reference Code – to specify the standards for individual aerodrome facilities suitable for use by different aircraft performance categories. The coding is reproduced in Error! Reference source not found..

Table 6 MOS Part 139 Extract – Table 2.1-2 Aerodrome Reference Code

Aerodrome Reference Code				
Code element 1		Code element 2		
Code number	Aeroplane reference field length	Code letter	Wing span	Outer main gear wheel span
1	Less than 800 m	A	Up to but not including 15 m	Up to but not including 4.5 m
2	800 m up to but not including 1200 m	B	15 m up to but not including 24 m	4.5 m up to but not including 6 m
3	1200 m up to but not including 1800 m	C	24 m up to but not including 36 m	6 m up to but not including 9 m
4	1800 m and over	D	36 m up to but not including 52 m	9 m up to but not including 14 m
		E	52 m up to but not including 65 m	9 m up to but not including 14 m
		F	65 m up to but not including 80 m	14 m up to but not including 16 m

Runway width and the strip running either side of the runway are important determinants of the lateral extent of the **OLS**. These are specified in Error! Reference source not found. and Error! Reference source not found. (for a precision approach runway) respectively.

Table 7 MOS Part 139 Extract – Table 6.201 Minimum Runway Width (m)

Code number	Code letter					
	A	B	C	D	E	F
1[a]	18 m	18 m	23 m	–	–	–
2	23 m	23 m	30 m	–	–	–
3	30 m	30 m	30 m	45 m	–	–
4	–	–	45 m	45 m	45 m	60 m

Note: 1. [a] Runway width may be reduced to 15 m or 10 m depending on the restrictions placed on small aeroplane operations. See Chapter 13.

Table 8 MOS Part 139 Extract – Table 6.2-7 Precision Approach Runway Strip Width (m)

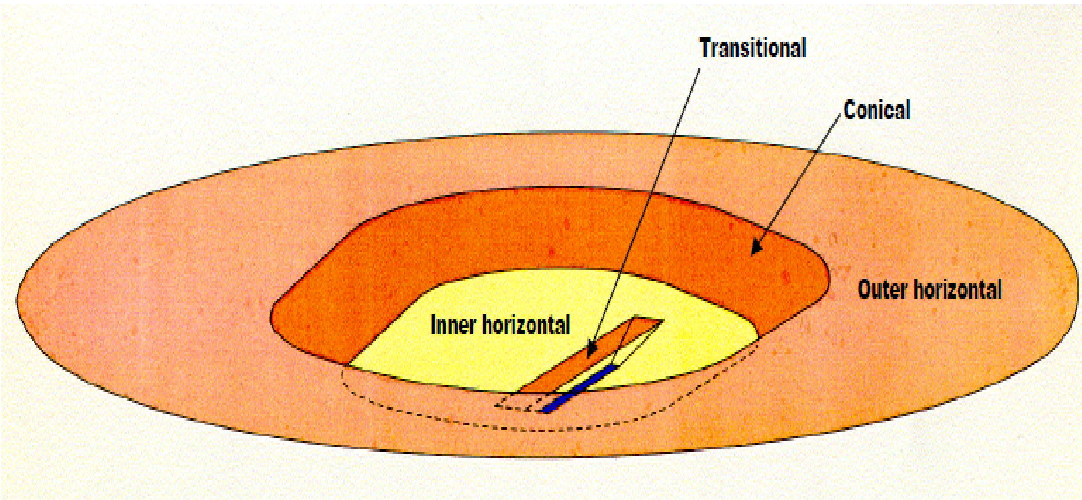
Aerodrome reference code	Overall runway strip width
1 or 2	150 m
3 or 4	300 m

C.6 Obstacle Limitation Surfaces

The **Obstacle Limitation Surfaces (OLS)** are conceptual (imaginary) surfaces associated with a runway, which identify the lower limits of the aerodrome airspace above which objects become obstacles to aircraft operations, and must be reported to **CASA**. The **OLS** is shown in a 3-D illustrative view in Error! Reference source not found. and comprises the following:

- outer horizontal surface;
- conical surface;
- inner horizontal surface;
- approach surface;
- inner approach surface;
- transitional surface;
- inner transitional surface;
- baulked landing surface; and
- take-off climb surface.

Figure C1 OLS Illustrative View



The dimensions recommended for various aerodrome code classifications have been reproduced in **Table 9**.

AUSTRALIA'S REGULATORY FRAMEWORK IN RELATION TO RESTRICTIONS ON SITING OF AIRPORT BUILDINGS

Table 9 MOS Part 139 Extract – Table 7.1-1 Aerodrome / Runway Critical Dimensions

OLS & Dimensions (in metres and percentages)	Runway Classification									
	Non-instrument				Instrument					
					Non-precision			Precision		
	Code No				Code No			I Code No		II & III Code No
	1*	2	3	4	1, 2	3	4	1, 2	3, 4	3, 4
OUTER HORIZONTAL										
Height (m)									150	150
Radius (m)									15000	15000
CONICAL										
Slope	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%
Height (m)	35	55	75	100	60	75	100	60	100	100
INNER HORIZONTAL										
Height (m)	45	45	45	45	45	45	45	45	45	45
Radius (m)	2000	2500	4000	4000	3500	4000	4000	3500	4000	4000
APPROACH										
Length of inner edge (m)	60	80	150[a]	150	90	150	300[b]	150	300	300
Distance from threshold (m)	30	60	60	60	60	60	60	60	60	60
Divergence each side	10%	10%	10%	10%	15%	15%	15%	15%	15%	15%
First section length (m)	1600	2500	3000	3000	2500	3000	3000	3000	3000	3000
Slope	5%	4%	3.33%	2.5%	3.33%	3.33%	2%	2.5%	2%	2%
Second section length (m)	-	-	-	-	-	3600[c]	3600	12000	3600	3600
Slope	-	-	-	-	-	2.5%[c]	2.5%	3%	2.5%	2.5%
Horizontal section length (m)	-	-	-	-	-	8400[c]	8400	-	8400	8400
Total length (m)	1600	2500	3000	3000	2500	15000[d]	15000	15000	15000	15000
INNER APPROACH										
Width (m)								90	120	120
Distance from threshold (m)								60	60	60
Length (m)								900	900	900
Slope								2.5%	2%	2%
TRANSITIONAL										
Slope	20%	20%	14.3%	14.3%	20%	14.3%	14.3%	14.3%	14.3%	14.3%
INNER TRANSITIONAL										
Slope								40%	33.3%	33.3%
BAULKED LANDING										
Length of inner edge (m)								90	120	120
Distance from threshold (m)								[e]	1800[f]	1800
Divergence each side								10%	10%	10%
S										3.3%

All distances are measured horizontally unless otherwise specified.

* Runways used for RPT operations at night by aircraft with maximum take-off mass not exceeding 5,700 kg are required to meet code 2 standards.

[a] 90 m where width of runway is 30 m.

[b] 150 m if only used by aeroplanes requiring 30 m wide runway.

[c] No actual ground survey required unless specifically required by procedure designer. Procedure designer will use topographical maps and tall structure databank to determine minimum altitudes.

[d] Approach area up to this distance needs to be monitored for new obstacles. Refer to procedure designer's advice on significant high ground or tall structure that needs monitoring.

[e] Distance to end of runway strip.

[f] Or to the end of the runway strip, whichever is less.

AUSTRALIA'S REGULATORY FRAMEWORK IN RELATION TO RESTRICTIONS ON SITING OF AIRPORT BUILDINGS

Of particular interest to the issue of building-induced windshear is the section of **OLS** adjacent and perpendicular to the ends of a runway (where the associated crosswind disturbance is most critical).

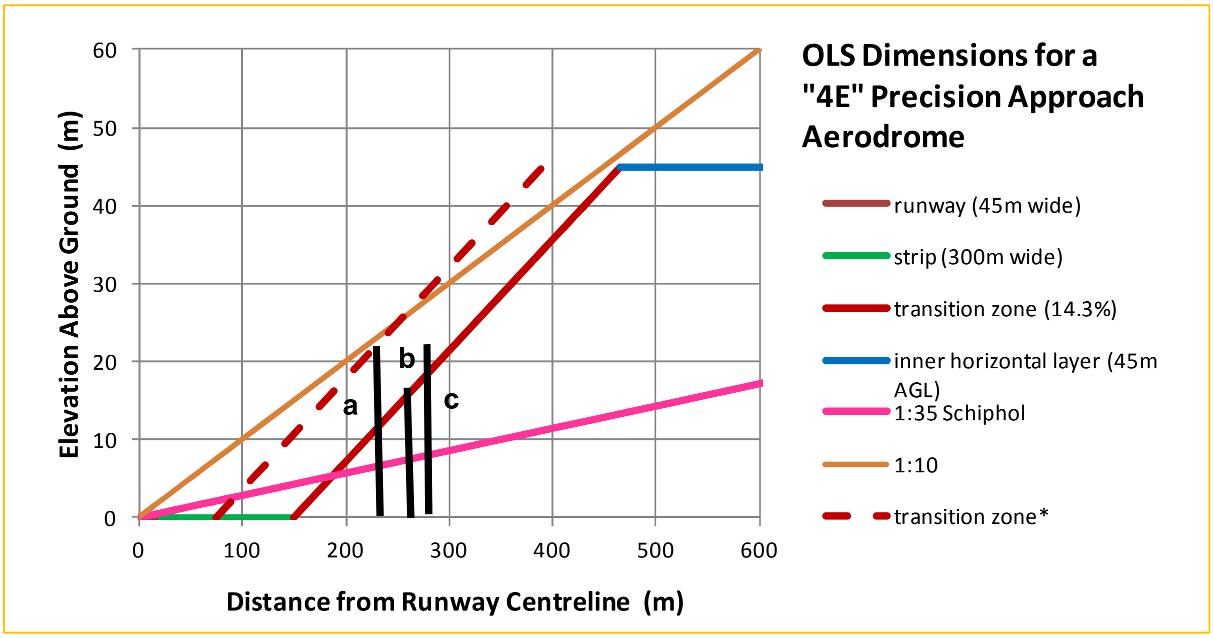
A sectional view of the OLS for a type "4E" runway classification is shown in **Figure C2** – refer **Table 9** for derivation of critical "4E" dimensions. It may be noted that the height of the Inner Horizontal Surface is 45 m for ALL airport code numbers.

Two transitional surfaces are shown in **Figure C2**, one for a "4E" precision approach runway (solid "brown" line) with a runway strip width of 300 m, the other (dashed "brown" line) for a runway width strip of 150 m applicable to non-precision approach runways.

Figure C2 also shows two alternative limiting surfaces, a plane of slope 1:35 out from the runway centreline (labelled the "Schiphol" boundary) and a plane of slope 1:10 out from the runway centreline (labelled the "SACL" boundary).

Finally three solid black lines indicate the nearest distance from runway and height of three "obstacles" of interest to this study: (a) Majura Park buildings located close to runway 12 at Canberra Airport, (b) the engine test run facility located close to runway 27 at Schiphol Airport, and (c) Hangar building located close to runway 35 at Canberra Airport.

Figure C2 Close-up View of Inner Parts of the OLS



From information provided in other sections of this report, it can be seen that ALL of these obstacles - (a), (b) and (c) - have generated documented incidents associated with building-induced windshear (and turbulence).

It is noted that all three buildings satisfied the 1:10 "simple" building height "rule" currently being used at a number of Australian airports.

C.7 Shielded Obstacles

A new obstacle may be assessed as not imposing additional restrictions if it does not exceed the height of an existing obstacle which is close to the runway strip and is perpendicularly behind the existing obstacle relative to the runway centre line – as illustrated in **Figure C3**.

Figure C3 Illustration of Obstacle Shielding Relative to the OLS