ENVIRONMENTAL WIND SPEED MEASUREMENTS ON A WIND TUNNEL MODEL OF THE 26-28 SHEPHERD STREET DEVELOPMENT, LIVERPOOL

by

A. Loie

and

M. Eaddy

SUMMARY

Wind tunnel tests have been conducted on a 1/400 scale model of the proposed 26-28 Shepherd Street Development, Liverpool, to provide data on environmental wind conditions at ground level. The model of the Development, within surrounding buildings including the 20 and 32-34 Shepherd Street developments, was tested in a simulated upstream boundary layer of the natural wind. The wind conditions measured have been related to the free stream mean wind speed at a reference height of 300m and compared with criteria developed for the Liverpool region as a function of wind direction.

The wind conditions for the Basic Configuration at most Test Locations have been shown to be either on or within the criterion for walking comfort for all wind directions, with many wind directions achieving the criteria for stationary activities. Several Test Locations were shown to have wind conditions above the criterion for walking comfort in the Basic Configuration, but the addition of the proposed tree landscaping improved the wind conditions to be either on or within the criterion for walking comfort for all wind directions.

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26-28 SHEPHERD STREET, LIVERPOOL
ENVIRONMENTAL WIND SPEED MEASUREMENTS

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CONTENTS

1. INTRODUCTION

The proposed 26-28 Shepherd Street Development will consist of 3 residential apartment towers (approximately 51m, 22m, and 72m in height) located on a riverside site near the south-west corner of the Shepherd and Atkinson Streets intersection in Liverpool. Figure 1 shows an aerial photograph of the site and surrounding buildings.

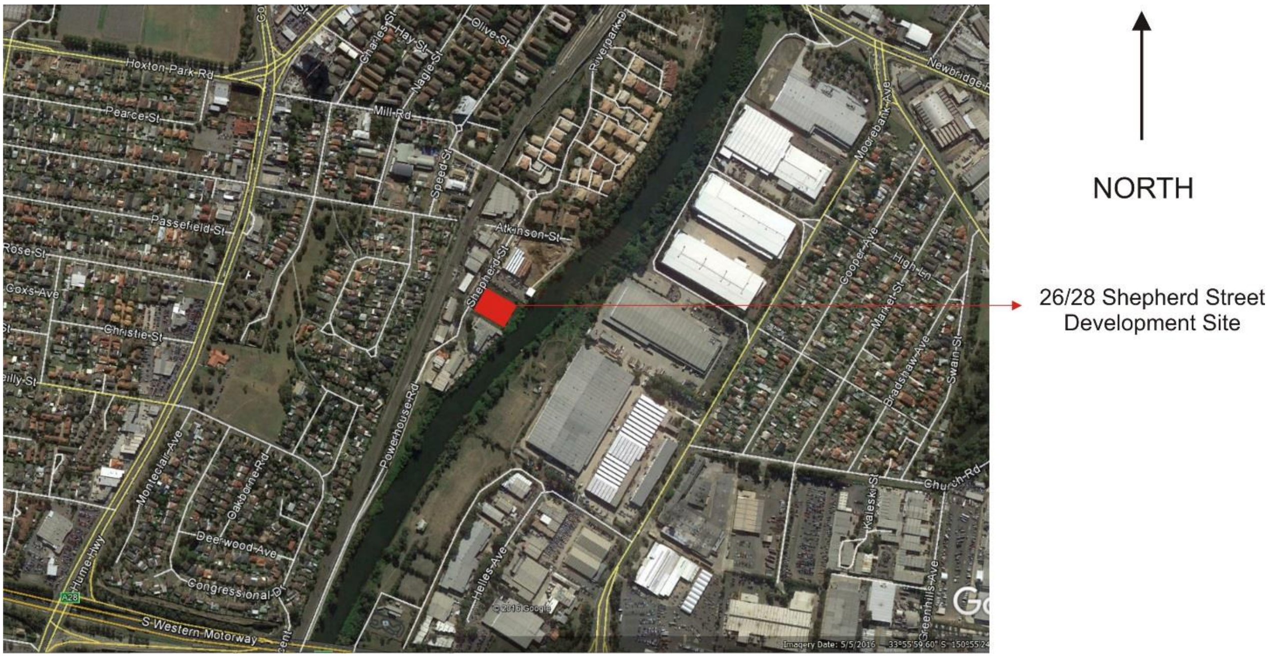

Figure 1 - Aerial view of the surrounding area of the 26-28 Shepherd Street Development.

A wind tunnel model study was commissioned by Coronation Property Co. P/L to undertake measurements of environmental wind conditions around the proposed development and, if necessary, develop wind amelioration features.

These tests were carried out in the MEL Consultants 400kW Boundary Layer Wind Tunnel during October 2016.

2. ENVIRONMENTAL WIND CRITERIA

The advancement of wind tunnel testing techniques, using large boundary layer flows to simulate the natural wind, has facilitated the prediction of wind speeds likely to be induced around a Development. To assess whether the predicted wind conditions are likely to be acceptable or not, some form of criteria are required. A discussion of criteria for environmental wind conditions has been made in a paper by Melbourne, Reference 1. This paper notes that it is the forces caused by the peak gust wind speeds and associated gradients which people feel most and criteria have been stated in terms of gust wind speeds. The probabilistic inference of these criteria in relation to hourly mean wind speeds and frequency of occurrence is discussed. The basic criteria can be summarised as follows:

In main public access-ways wind conditions are considered

(a) unacceptable if the peak gust speed during the hourly mean with a probability of exceedence of 0.1% in any 22.5^o wind direction sector exceeds 23ms^{-1} (the gust wind speed at which people begin to get blown over);

(b) generally acceptable for walking in urban and suburban areas if the peak gust speed during the hourly mean with a probability of exceedence of 0.1% in any 22.5^o wind direction sector does not exceed 16 ms^{-1} (which results in half the wind pressure of a 23 ms^{-1} gust).

For more recreational activities wind conditions are considered

(c) generally acceptable for stationary short exposure activities (window shopping, standing or sitting in plazas) if the peak gust speed during the hourly mean with a probability of exceedence of 0.1% in any 22.5^o wind direction sector does not exceed 13 ms^{-1};

(d) generally acceptable for stationary, long exposure activities (outdoor restaurants, theatres) if the peak gust speed during the hourly mean with a probability of exceedence of 0.1% in any 22.5^{o} wind direction sector does not exceed 10 ms^{-1}.

The probability of exceedence of 0.1% relates approximately to the annual maximum mean wind speed occurrence for each wind direction sector. These criteria can be developed in terms of hourly mean wind speed versus frequency of occurrence as shown in References 1 and 2.

The above criteria are the criteria outlined in the Liverpool Development Control Plan (DCP) 2008 but with more detailed definitions. It would be expected that the Liverpool DCP have sourced these criteria from the City of Sydney DCP criteria, which have their origin form the paper by Melbourne reference above and provided in Appendix A.

For the purpose of comparison, or integrating with local wind data, it is necessary to be able to relate the local velocity measurement to a reference velocity well clear of the influence of buildings. Because the wind force is related to wind velocity squared, it is often more convenient to express criteria in terms of velocity ratio squared, or velocity pressure ratio as this becomes. To this end, two velocity pressure ratios referenced to conditions at 300m height in suburban terrain [terrain category 3] (as a convenient reference) are defined as,

mean velocity pressure ratio $$\left|\frac{\bar{V}_{local}}{\bar{V}_{300m}}\right|^2$$

and

peak velocity pressure ratio $$\left|\frac{\hat{V}_{local}}{\bar{V}_{300m}}\right|^2$$

where the peak velocity is the 3-second mean maximum gust wind speed in full scale conditions.

For wind conditions in Liverpool these criteria can be expressed in terms of velocity pressure ratios, calculated from hourly mean wind speed data as per the methodology given in Reference 1. Corrections have been made where long distance approach terrain is different to Terrain Category 3.

The criteria in terms of peak velocity pressure ratios are illustrated in Figure 2 and appear in subsequent figures to enable immediate assessment of the wind conditions as measured on the model.

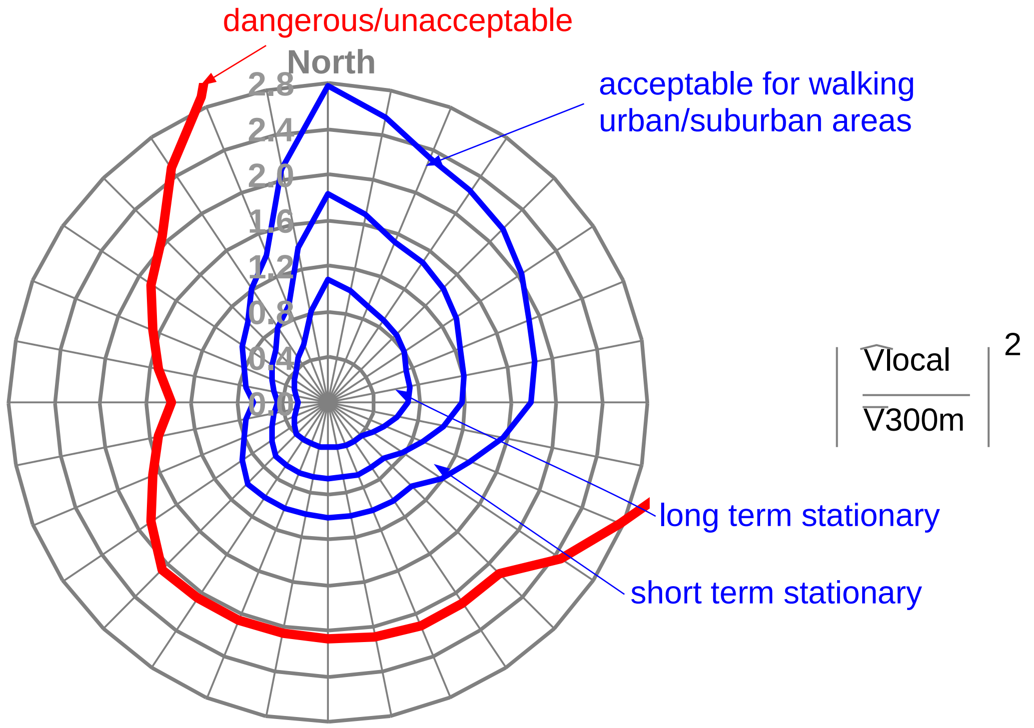

Figure 2- Environmental wind criteria for Liverpool expressed in terms of peak velocity pressure ratios

The velocity pressure ratio values considered as unacceptable in Figure 2 are equivalent to conditions which have existed in some areas in Australian capital cities where people have been blown over by the wind. The velocity pressure ratios considered as acceptable for walking in urban and suburban areas are equivalent to conditions existing at corners in these areas before high rise development commenced.

3. TERRAIN ANALYSIS

The Development site is surrounded mostly by residential dwellings and warehouses for all wind directions which means that the approach flow would be Terrain Category 3 for all wind directions as illustrated in Figure 3.

Figure 3 - Aerial view of the site location and surrounding buildings within a radius 300m from the 26-28 Shepherd Street Development.

4. MODEL AND EXPERIMENTAL TECHNIQUES

A 1/400 scale model of the 26-28 Shepherd Street development was constructed from drawings by Woods Bagot dated 16 September, 2016. Subsequent drawings dated 8 December, 2016, have made only minor changes to the built form and, from an environmental wind perspective, would be the same built form used to the wind tunnel model.

The scale model of the 26-28 Shepherd Street Development and surrounding buildings, including the under construction 20 Shepherd Street and the proposed 32-34 Shepherd Street developments, were tested in a model of the natural wind generated by flow over roughness elements augmented by vorticity generators at the entrance of the wind tunnel working section. The basic natural wind model was for flow over suburban terrain roughness, which had a mean velocity power law profile with an exponent of 0.2, i.e. $\overline{V}_z = f(z)^{0.2}$ and a turbulence intensity at a scaled height of 100m of $\sigma_v/\overline{V} =$ 0.17, as shown in Figure 4. Photographs of the model building are shown in Figures 5 and 6.

The techniques used to investigate the environmental wind conditions and the method of determining the local criteria are given in detail in Reference 2. In these tests measurements in the Development areas are inside separated regions and peak velocity squared ratios were required to make conclusions about likely wind conditions. In summary, measurements were made of the peak gust wind velocity with a hot wire anemometer at various stations and expressed as a squared ratio with the mean wind velocity at a scaled reference height of 300m. This gives the peak velocity squared ratio

$$\left(\hat{V}_{local}/\overline{V}_{300m}\right)^2$$

as defined in Section 2. This peak velocity squared ratio can then be compared with the velocity squared ratio criteria for Liverpool given in Figure 2. Wind tunnel velocity measurements were made for an equivalent 1 hour period in full scale and filtered to provide an equivalent full scale 3 second gust wind speed.

Measurements were made at various locations in and around the development, for different wind directions at 22.5° intervals. Turbulent gusty wind flows, caused by separated flows, were generally observed with a combination of low and high mean wind speeds. To quantify this, peak gust wind speeds were measured, using the hot wire anemometer, and related to the environmental wind criteria via the calculated peak velocity squared ratios. The results of these measurements are presented on polar diagrams against a background plot of the various criteria for each Test Location. The Test Locations are shown in Figure 7.

5. DISCUSSION OF RESULTS

The Basic Configuration for the development is as outlined in the drawings by Woods Bagot dated 16 September, 2016. Testing was conducted in two phases. Initially without the use of trees, and then incorporating the landscaping scheme provided as the form of wind mitigation.

The tree landscaping was only included where the wind conditions for the Basic Configuration were found to be above the above the criterion for walking comfort. They required the following characteristics:

- Dense evergreen (minimum 80% solidity) canopies.
- Tree canopies within 200-300mm of the building facade as shown in Figure 7.
- Tree canopies starting approximately 2.5m above ground level.
- Continuous tree canopies (i.e. each tree canopy must connect with neighbouring tree canopies) over the extent shown in Figure 7.
- Existing Trees and foliage along the west side of the river bank to be retained where possible.

Where the wind conditions for the Basic Configuration achieved the criterion for walking comfort, then the conditions with the trees would be better than those presented in the Report.

It should be noted that the wind conditions presented for the Basic Configuration with Trees are for the fully mature trees that satisfy the above requirements. If the trees fail to reach the required size and density or are planted as immature trees then the wind conditions would deteriorate towards those of the Basic Configuration.

The following Sections detail the results for the various areas tested.

5.1. Summary of discussion (Figures 8 and 9)

To assist with the assessment of the pedestrian level wind conditions, a summary of the highest wind comfort criteria at each Test Location for all wind directions (i.e. 0°→ 360°) at ground level for the Basic Configuration without trees and with trees has been provided in Figures 8 and 9. Different colours have been used to represent the highest wind criteria achieved at the respective Test Locations.

5.2. Shepherd Street (Figures 10 and 11)

The wind conditions for the Basic Configuration at Test Locations 28, 10, 9, 8, 21, 20, and 25 have been shown to be either on or within the criterion for walking comfort for all wind directions, with many wind directions achieving the criteria for stationary activities.

5.3. Laneway adjacent to 20 Shepherd Street (Figure 12)

The wind conditions for the Basic Configuration at Test Locations 19, 23, and 24 have been shown to be either on or within the criterion for walking comfort for all wind directions with many wind directions achieving the criterion for stationary activities. The wind conditions at Test Location 23 have also been presented with the trees and show the improved the landscaping makes to the pedestrian level wind conditions.

5.4. Riverfront (Figure 13, 14, and 15)

The wind conditions for the Basic Configuration along the Riverfront (Test Locations 27, 26, 18, 17, 4, 3, 2, 1, 32, and 31 have been shown to be above the criterion at a number of locations for the westerly and south-easterly wind directions. The remaining wind directions have been shown to be either on or within the criterion for walking comfort. The wind conditions for the Basic Configuration with trees have been shown to be either on or within the criterion for walking comfort for all wind directions at all Test locations along the Riverfront. The wind conditions at many of the Test Location with the trees have been shown to achieve the criteria for stationary activities.

5.5. Laneway adjacent to 32-34 Shepherd Street (Figures 16 & 17)

The wind conditions for the Basic Configuration along the Laneway between 26-28 Shepherd Street and 32-34 Shepherd Street (Test Locations 30, 14, 15, 29, and 11) have been shown to be either on or within the criterion for walking comfort for all wind directions except for Test Locations 30 for the south-southwest and west wind directions. These wind directions at Test Location 30 have been shown to be above the criterion for walking comfort. However, the addition of the landscaping trees has been shown improve the wind conditions at Test Location 30 to be either on or within the criterion for walking comfort for all wind directions.

5.6. Laneway between 26 and 28 Shepherd Street (Figure 18)

The wind conditions for the Basic Configuration in the Laneway between 26 and 28 Shepherd Street (Test Locations 22, 5 and 7) have been shown to be either on or within the criterion for walking comfort criterion for all wind directions. It has also be shown with the addition of the landscaping trees at Test Locations 5 and 7 that the wind conditions for some directions improve.

5.7. Central Park (Figure 19)

The wind conditions for the Basic Configuration in the Central Park (Test Locations 6, 12, 13, and 16) have been shown to be either on or within the criterion for walking comfort criterion for all wind directions with many wind directions achieving the criteria for stationary activities. The proposed landscaping trees have been shown to improve the wind conditions at these Test Locations.

6. CONCLUSIONS

Wind tunnel tests have been conducted on a 1/400 scale model of the proposed 26-28 Shepherd Street Development, Liverpool, to provide data on environmental wind conditions at ground level. The model of the Development, within surrounding buildings including the 20 and 32-34 Shepherd Street developments, was tested in a simulated upstream boundary layer of the natural wind. The wind conditions measured have been related to the free stream mean wind speed at a reference height of 300m and compared with criteria developed for the Liverpool region as a function of wind direction.

The wind conditions for the Basic Configuration at most Test Locations have been shown to be either on or within the criterion for walking comfort for all wind directions, with many wind directions achieving the criteria for stationary activities. Several Test Locations were shown to have wind conditions above the criterion for walking comfort in the Basic Configuration, but the addition of the proposed tree landscaping improved the wind conditions to be either on or within the criterion for walking comfort for all wind directions.

M. Eaddy

MEL Consultants Pty Ltd

October 2016

REFERENCES

1. W. H. Melbourne, Criteria for environmental wind conditions, Journal of Industrial Aerodynamics, Volume 3, 1978, pp. 241-249
2. W. H. Melbourne, Wind environment studies in Australia, Journal of Industrial Aerodynamics, Volume 3, 1978, pp. 201-214

FIGURES

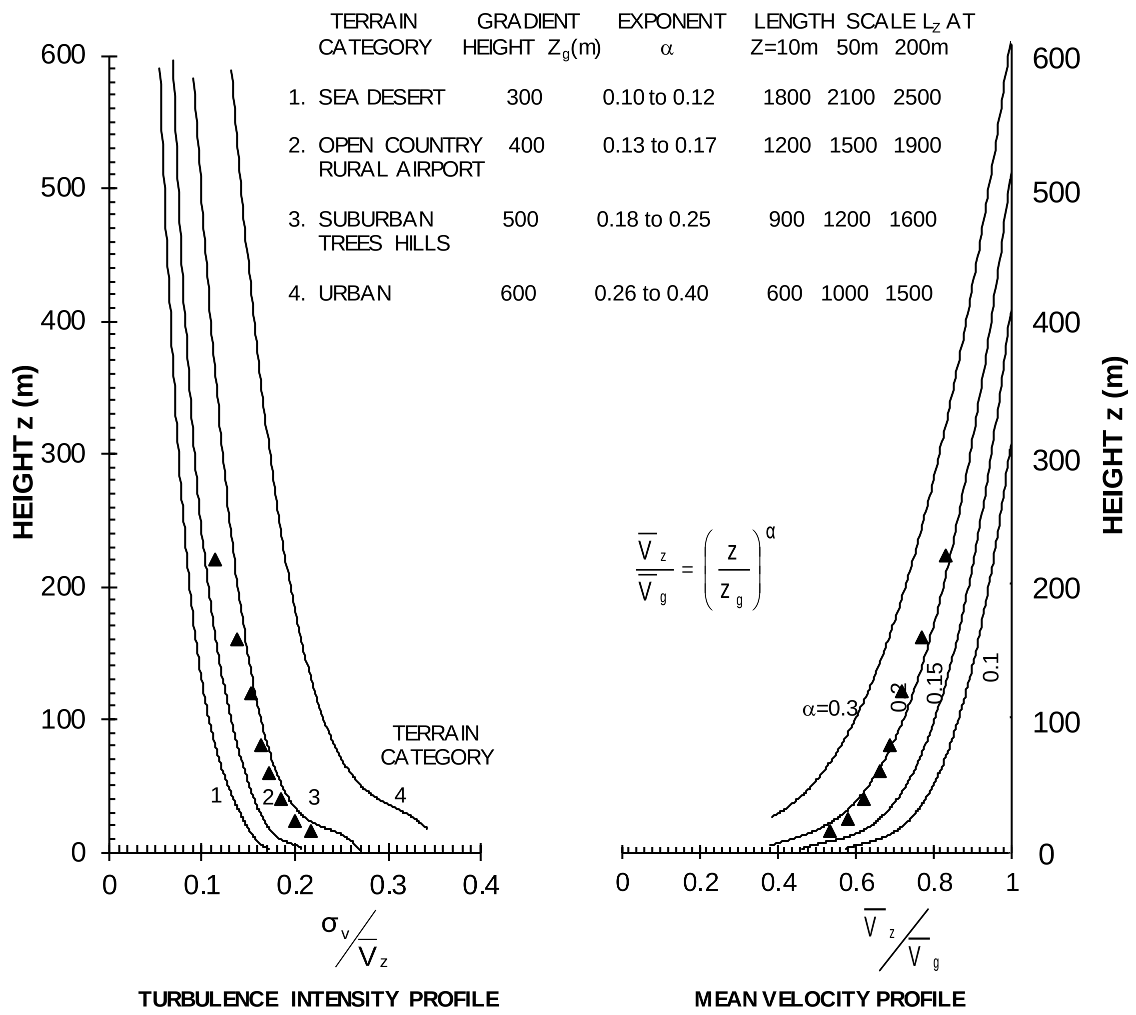

Figure 4 - 1/400 scale TC3 boundary layer turbulence intensity and mean velocity profiles and spectra in the MEL Consultants Boundary Layer Wind Tunnel 5m x 2.4m working section, scaled to full scale dimensions

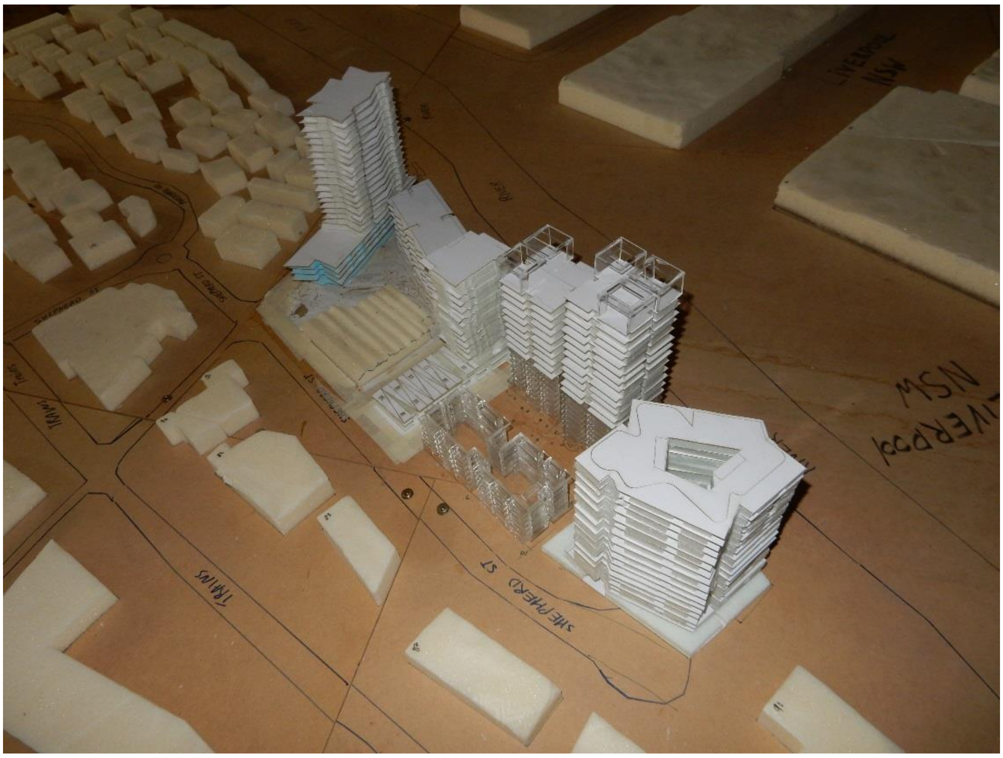

Figure 5 – View from the southwest of the scale model of the 26-28 Shepherd Street Development in the wind tunnel.

Figure 6 – View from the east of the scale model of the 26-28 Shepherd Street Development in the wind tunnel.

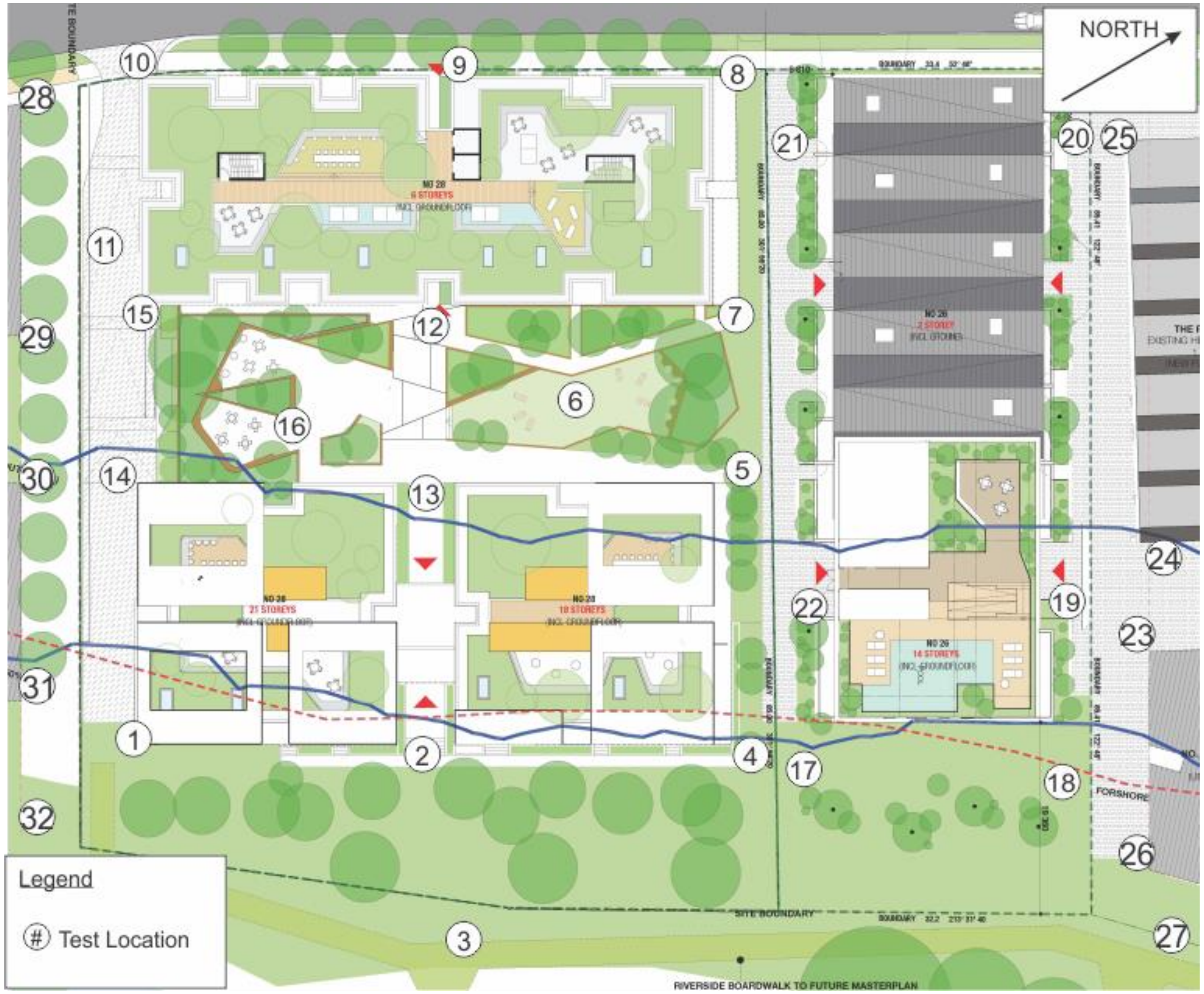

Figure 7 - Test Locations around the 26-28 Shepherd Street development

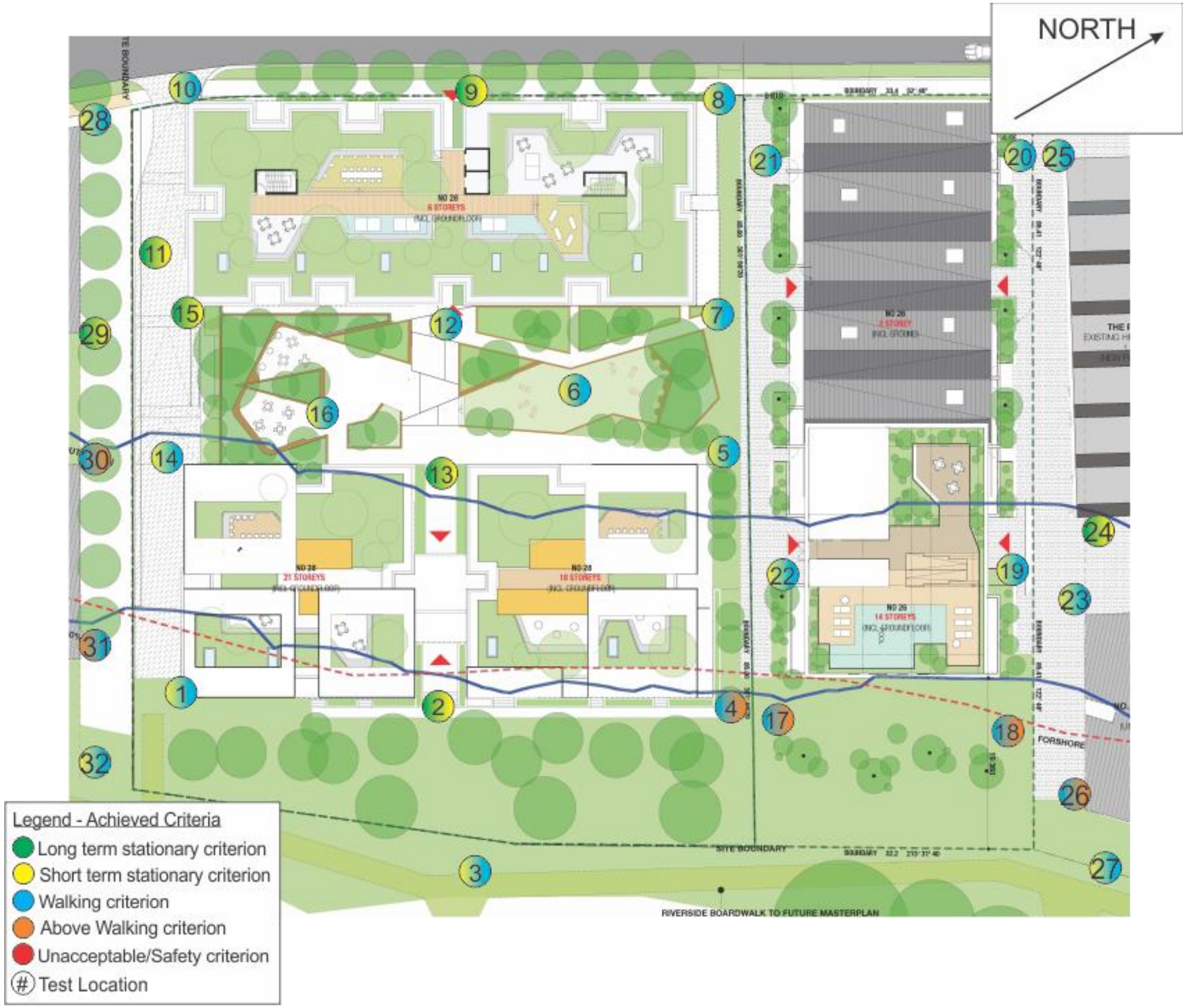

Figure 8 - Summary of the wind conditions for the Basic Configuration without Trees

Figure 9 - Summary of the wind conditions for the Basic Configuration with Trees

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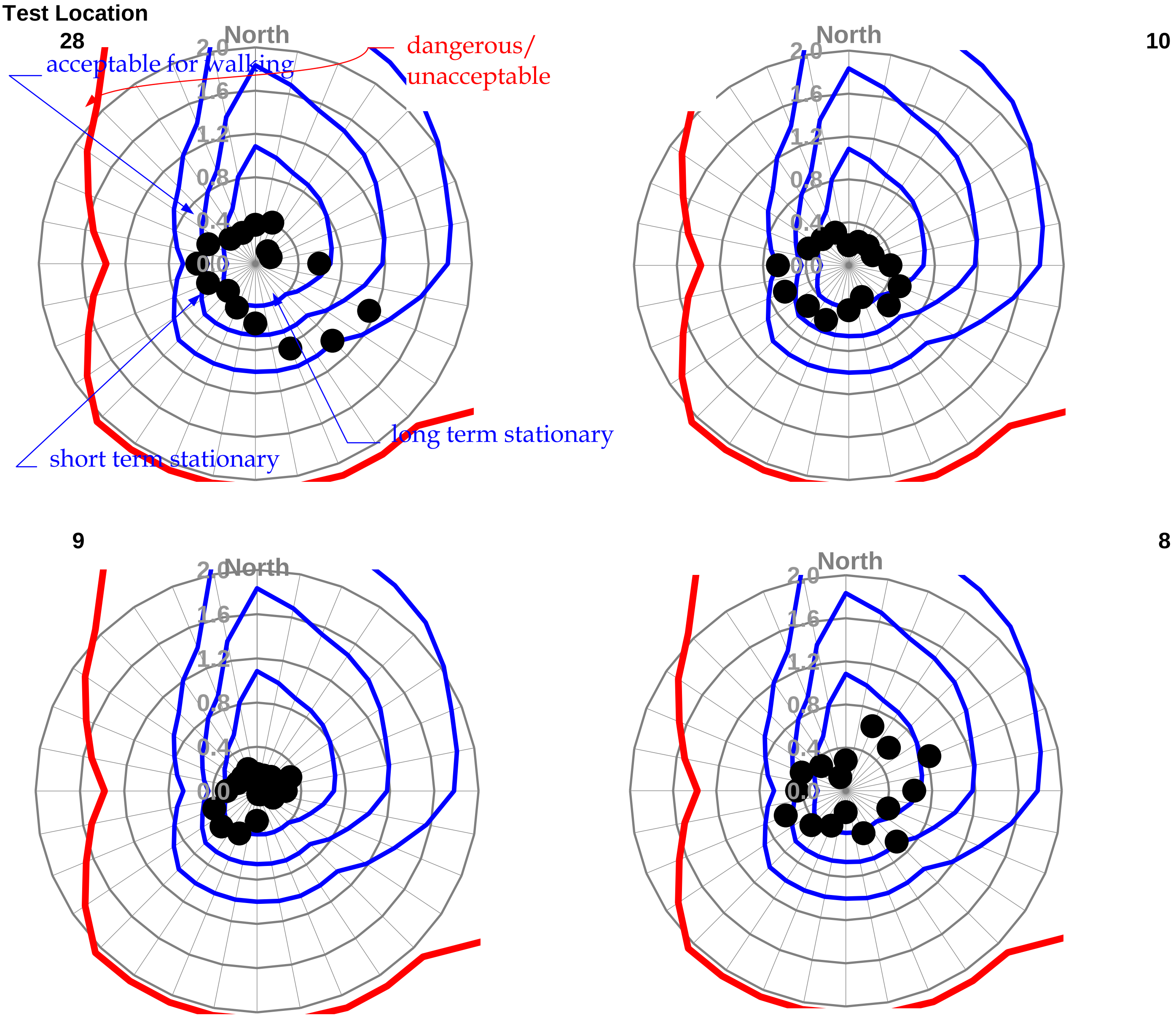
APPENDIX A – Reference Papers

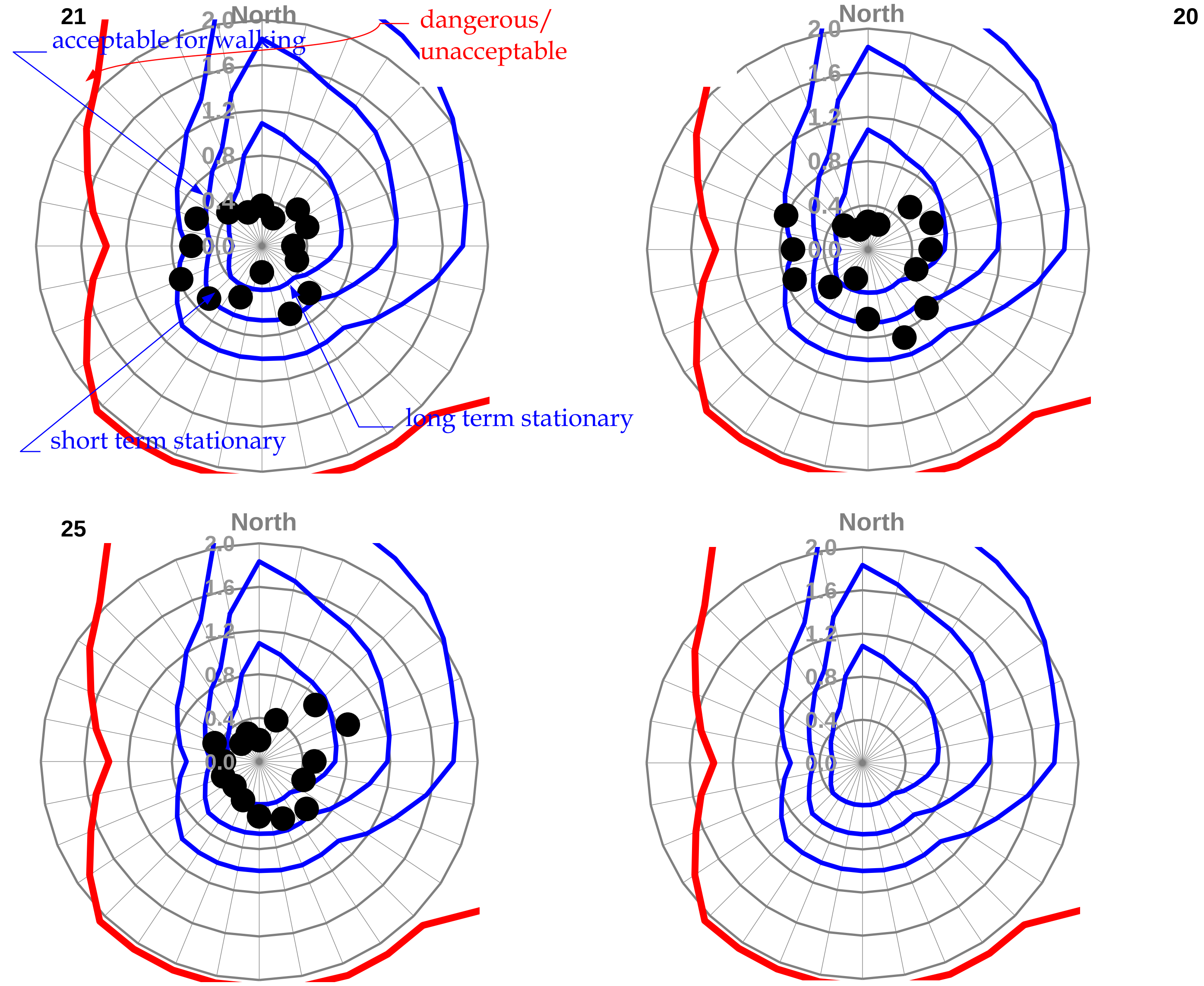


Peak velocity squared ratio $\left| \frac{\hat{V}_{local}}{\bar{V}_{300m}} \right|^2$ as a function of wind direction

Basic Configuration	● (black)
Basic Configuration + Trees	● (green)

Figure 10 - Shepherd Street

Test Location



Peak velocity squared ratio $\left|\frac{\hat{V}_{local}}{\overline{V}_{300m}}\right|^2$ as a function of wind direction

Basic Configuration ●
Basic Configuration + Trees ●

Figure 11 - Shepherd Street

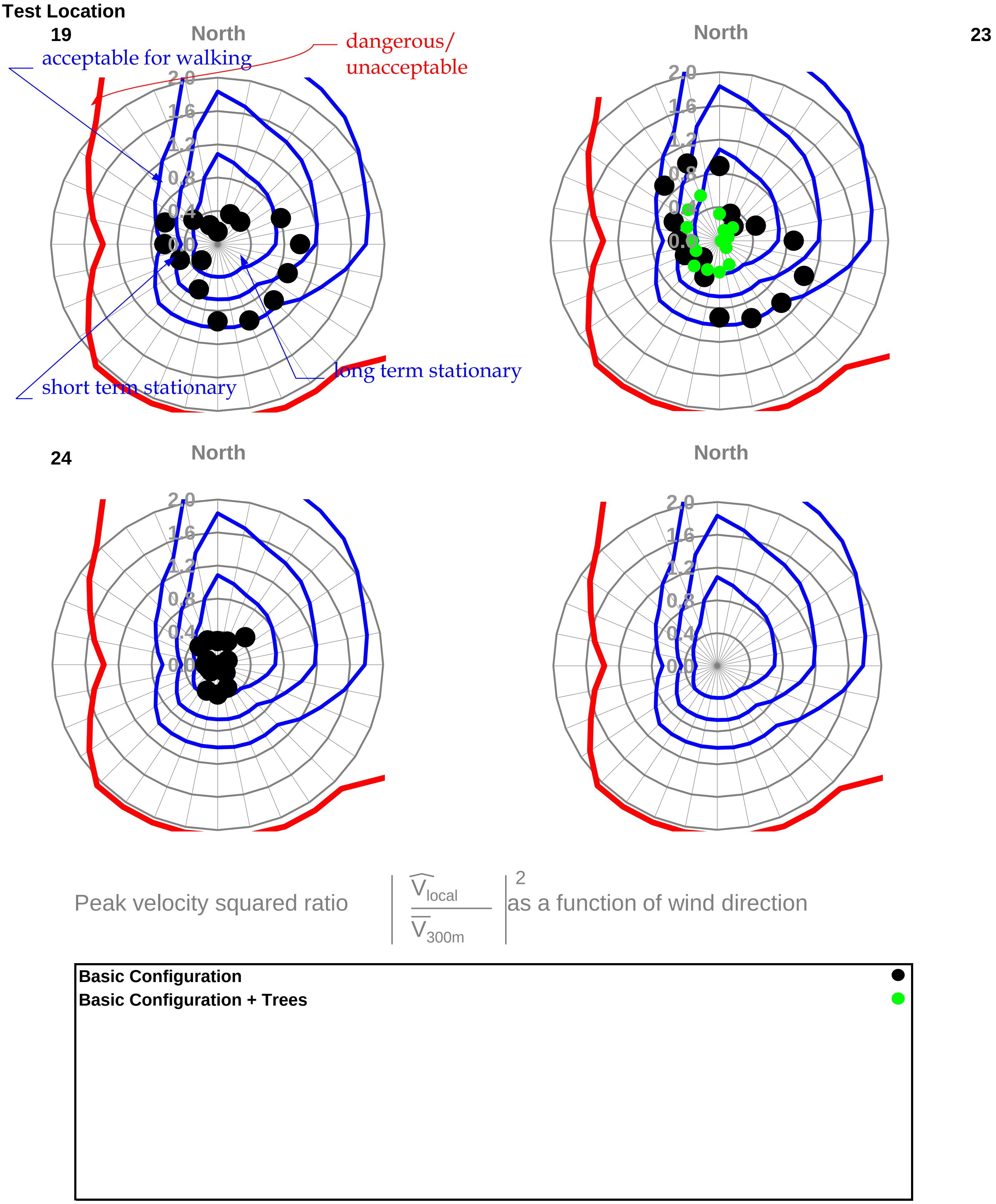
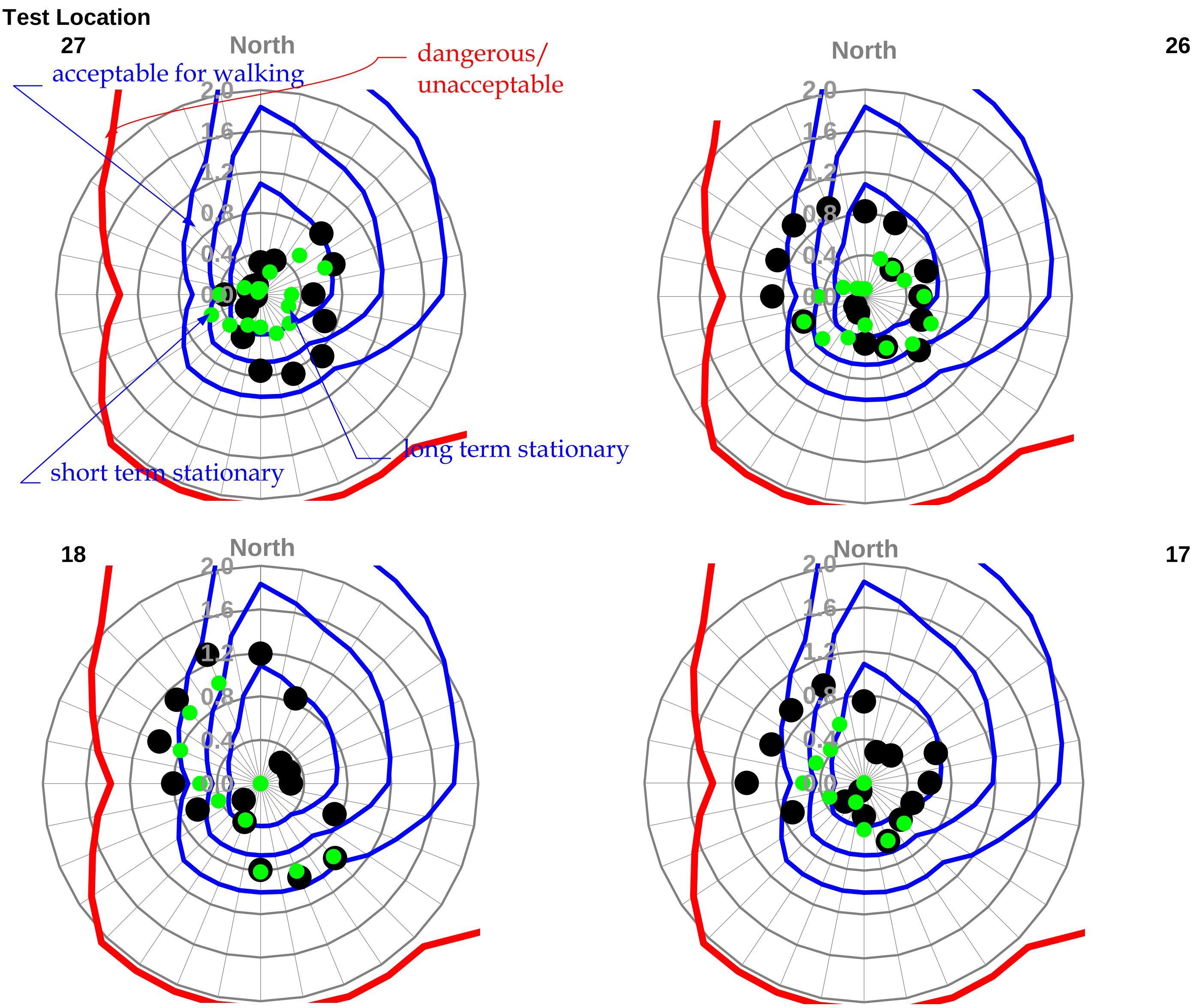


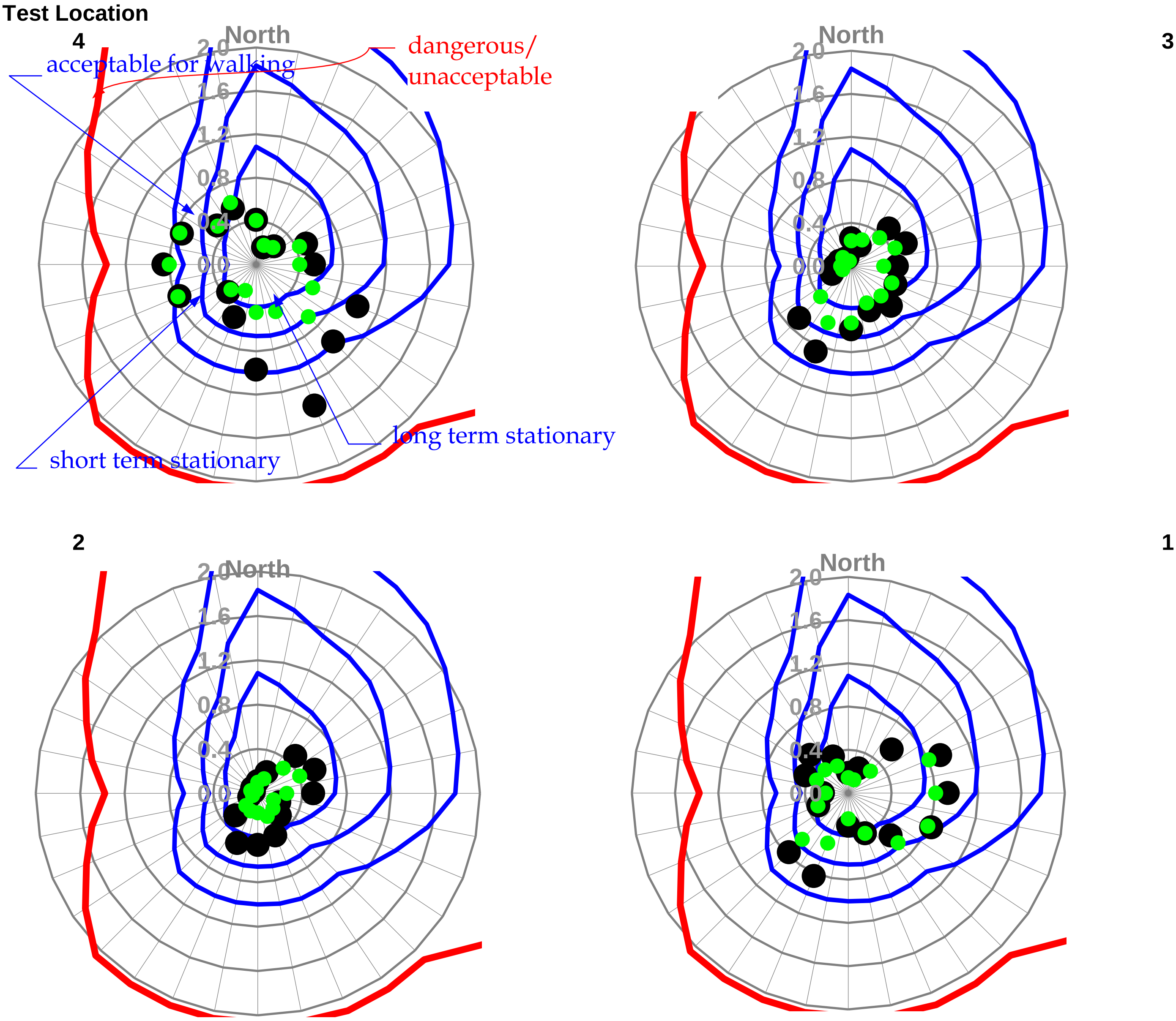
Figure 12 - Laneway adjacent to 20 Shepherd Street



Peak velocity squared ratio $\left| \frac{\widehat{V}_{local}}{\overline{V}_{300m}} \right|^2$ as a function of wind direction

Basic Configuration	● (black)
Basic Configuration + Trees	● (green)

Figure 13 - Riverfront

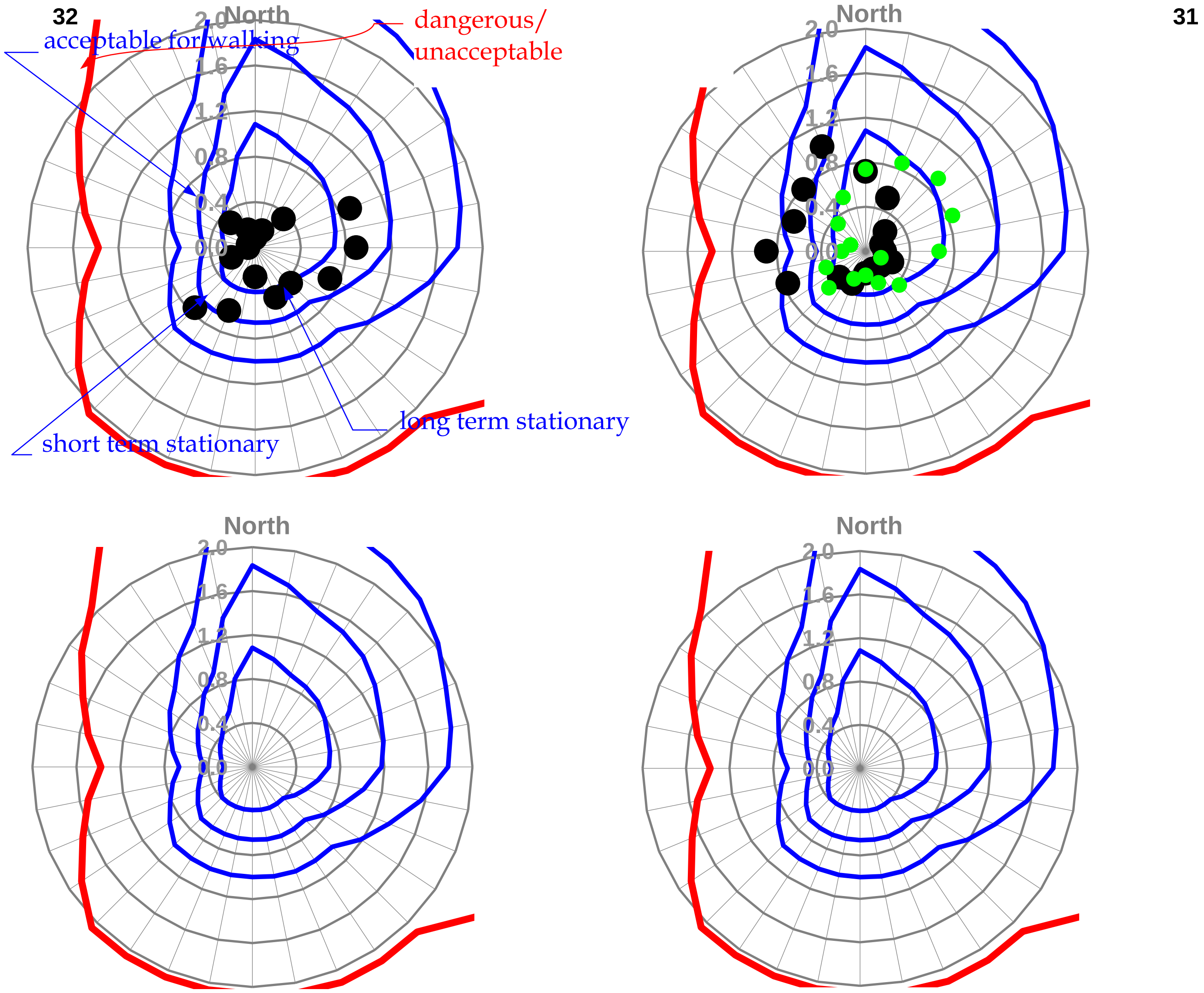


Peak velocity squared ratio $\left| \frac{\hat{V}_{local}}{\overline{V}_{300m}} \right|^2$ as a function of wind direction

Basic Configuration	● (black)
Basic Configuration + Trees	● (green)

Figure 14 - Riverfront [Continued]

Test Location



Peak velocity squared ratio $\left| \frac{\hat{V}_{local}}{\bar{V}_{300m}} \right|^2$ as a function of wind direction

Basic Configuration	●
Basic Configuration + Trees	● (green)

Figure 15 - Riverfront [Continued]

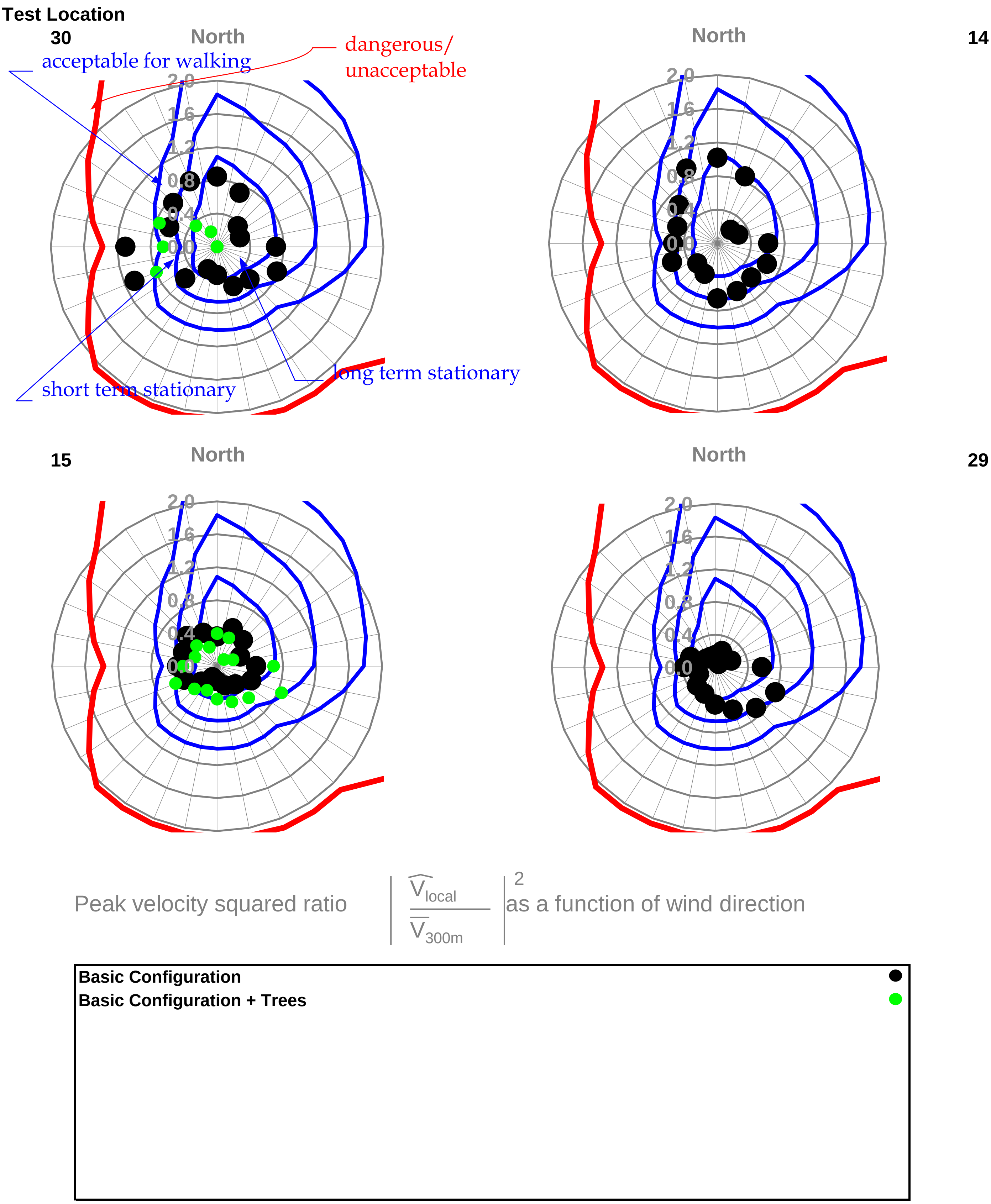
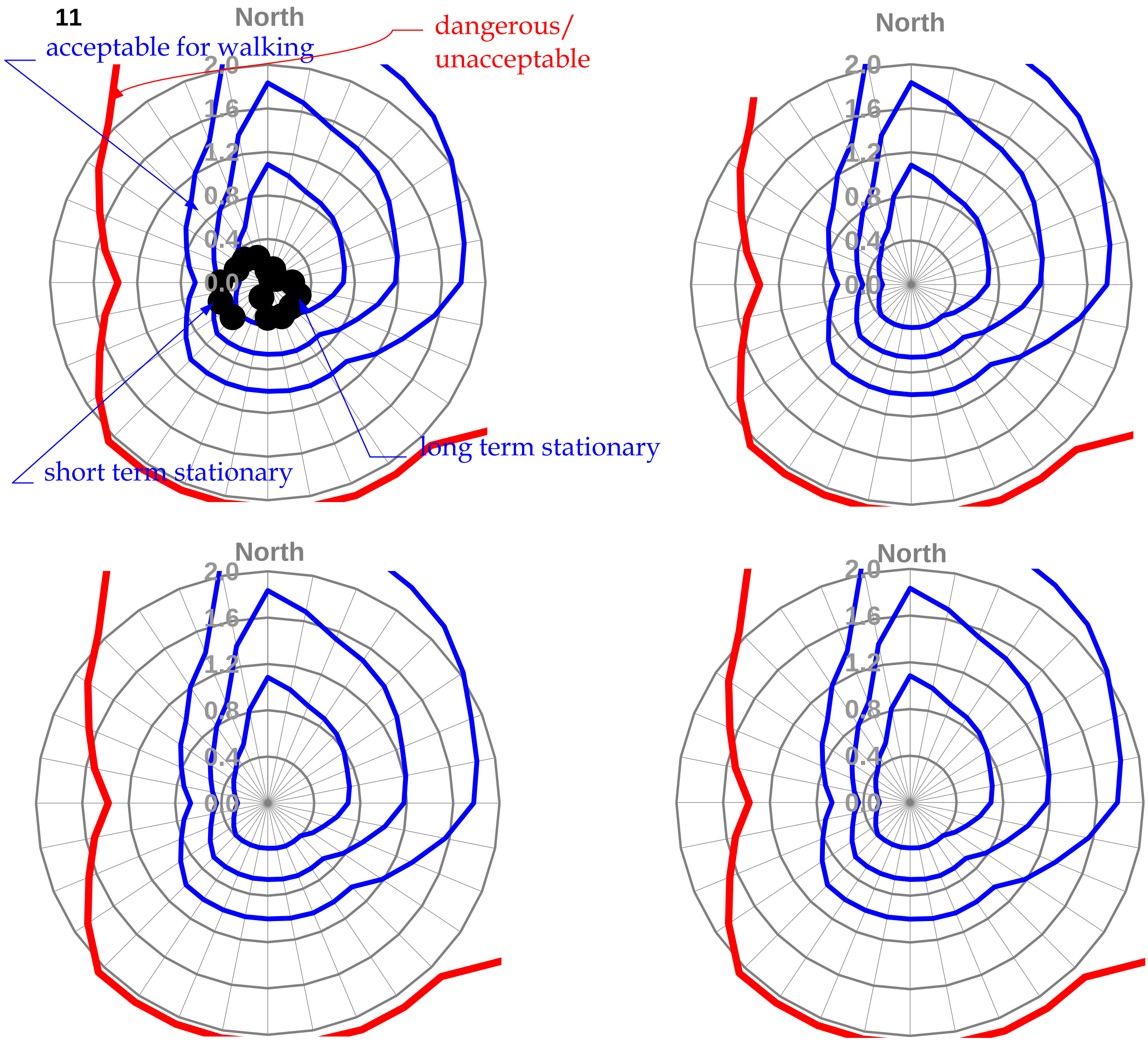


Figure 16 - Laneway adjacent to 32-34 Shepherd Street

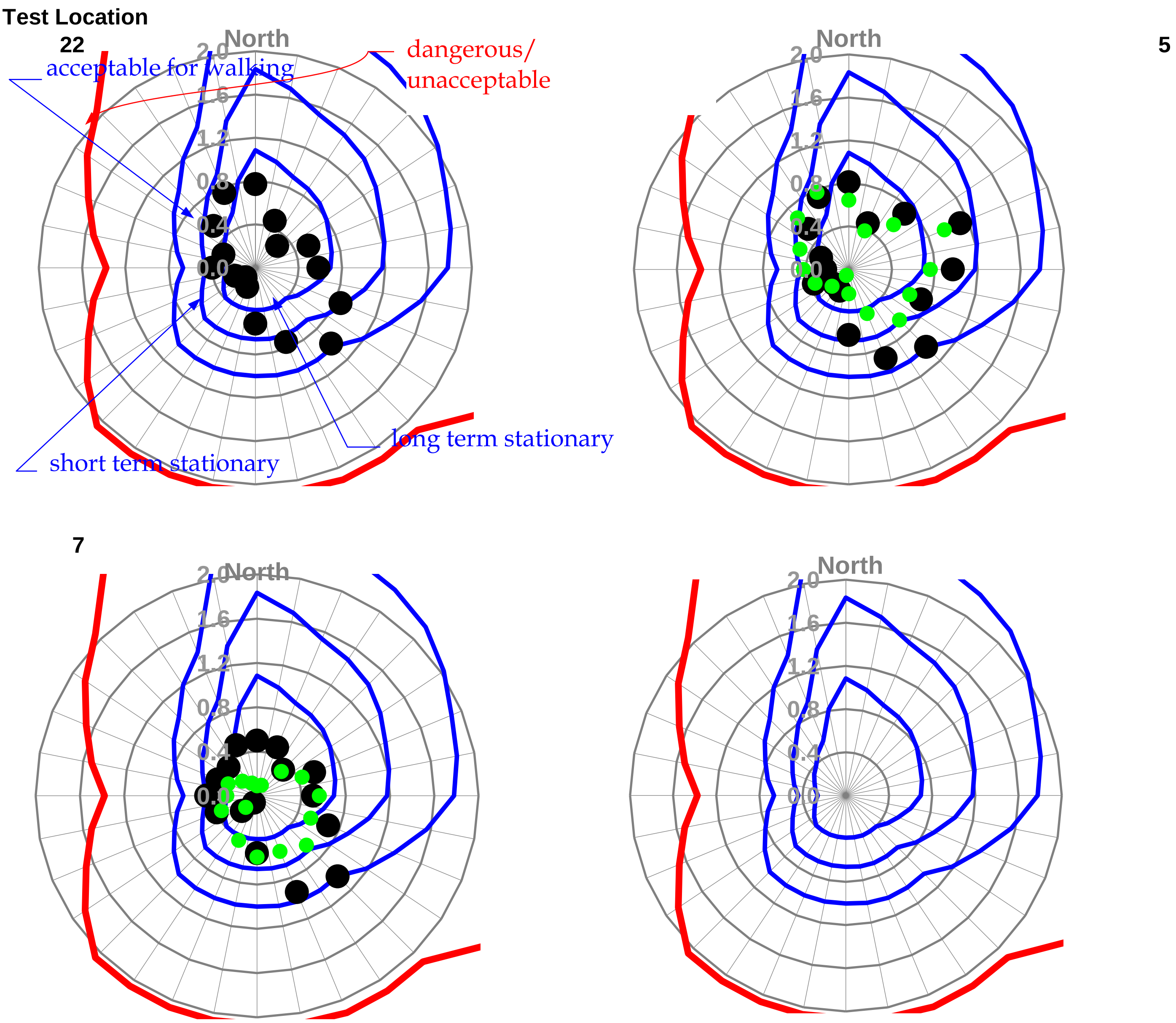
Test Location
11



Peak velocity squared ratio $\left|\frac{\hat{V}_{local}}{\bar{V}_{300m}}\right|^2$ as a function of wind direction

Basic Configuration	●
Basic Configuration + Trees	●

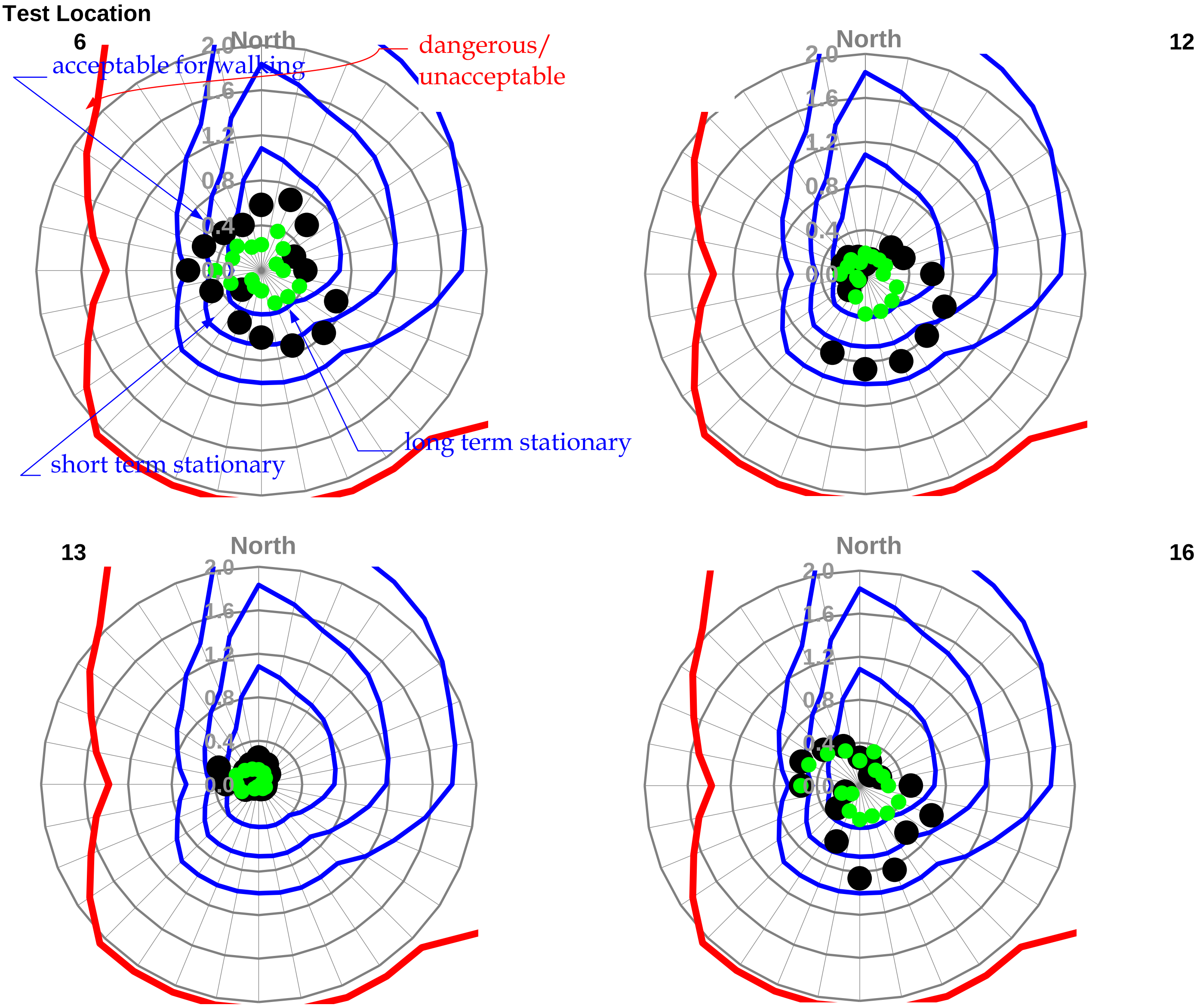
Figure 17 - Laneway adjacent to 32-34 Shepherd Street [Continued]



Peak velocity squared ratio $\left|\frac{\hat{V}_{local}}{\overline{V}_{300m}}\right|^2$ as a function of wind direction

Basic Configuration	● (black)
Basic Configuration + Trees	● (green)

Figure 18 - Laneway between 24 and 26 Shepherd Street



Peak velocity squared ratio $\left|\frac{\hat{V}_{local}}{\bar{V}_{300m}}\right|^{2}$ as a function of wind direction

Basic Configuration	●
Basic Configuration + Trees	●

Figure 19 - Central Park

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APPENDIX A – Reference Papers

Journal of Industrial Aerodynamics, 3 (1978) 241—249

Paper 12

CRITERIA FOR ENVIRONMENTAL WIND CONDITIONS

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(Received October 18, 1977)

Summary

Since 1971 a number of authors have published criteria for the acceptability of environmental wind conditions for human comfort for a range of activities.

This paper notes that it is the forces caused by peak gust wind speeds and associated gradients which people feel most and discusses the relation between peak gust and mean wind speeds. Melbourne's criteria, which have been stated in terms of maximum gust speeds per annum, are shown to define a range of wind-speed probabilities, in particular, the frequency of occurrence of mean wind speeds, which then facilitates comparison between the various published criteria.

It is shown that, in spite of the apparent numerical differences in published wind speed criteria and the various subjective assumptions used in their development, there is remarkably good agreement when they are compared on a proper probabilistic basis.

1. Introduction

In recent literature and at the 4th International Conference on Wind Effects on Buildings and Structures, London, 1975, there has been some debate as to the quantitative values of wind speed to be used in criteria for environmental conditions around new building developments. It was noted by several of the authors at the above-mentioned conference, that in spite of the seeming numerical differences in wind-speed criteria quoted by a number of authors, the differences were, in fact, relatively small [1]. The problem is that the phenomenon of wind and frequency of occurrence is very complex and the numerical values developed for these criteria depend on the statistical framework in which they are set.

It is the purpose of this paper to discuss the physical nature and effect of wind on people in respect of the relationship between mean wind speeds and peak gusts produced in turbulent conditions and the statistical inference of the various ways of expressing the frequency of occurrence of given wind speeds, and hence to permit a comparison of the various published environmental wind criteria.

2. The reason for needing environmental wind-speed criteria

Whilst involved in the technical argument about criteria, it is important to remember the reason for trying to establish environmental wind-speed criteria.

Briefly, the need has arisen because unacceptable wind speeds can be induced around building developments and one way of avoiding these problems is to conduct wind-tunnel tests from which wind speeds around a proposed development can be estimated. Having obtained the facility for predicting likely wind conditions in a given area, it becomes necessary to develop some criteria as to the frequency of occurrence of wind speeds which are acceptable and unacceptable for a variety of activities.

3. How people feel the effects of wind

There seems little doubt that wind speed and rate of change of wind speed are the primary parameters in any assessment of how wind affects people, Melbourne [2], Hunt et al. [3]. There are, of course, other factors such as temperature, humidity, degree of shade and mode of dress, which are also significant; however, these are factors which can be superimposed on or used to modify the effects of wind speed and as such will not be dealt with here.

Wind gustiness, or fluctuation of wind speed with time, is a random process and whilst the mean wind speed is a meaningful and simple parameter to obtain, the rate of change of wind speed is not. Fortunately, the effect of rate of change of wind speed can be covered generally by the parameter of turbulence intensity of wind speed, that is the standard deviation over the mean of wind speed. Further, in terms of what people feel, it is often convenient to talk in terms of a gust wind speed, that is a wind speed averaged over the smallest periods of time to which a person can respond, of the order of seconds. The mean 2- or 3-second-gust wind speed has become a useful reference in this respect, because it is roughly equivalent to the peak gust speed recorded by the Dines anemometer and the larger cup anemometers.

The wind force felt by a person is related to dynamic pressure. Hence, whilst it may be convenient in one sense to relate criteria directly to wind speed, it must be appreciated that the force felt by a person is proportional to wind speed squared. For this reason a more rational feel for the problem is gained if comparative data are presented in terms of velocity pressures rather than velocities. However, the referring of criteria to wind speed has gained popular acceptance and values of wind speed are more easily remembered than numbers based on the square of wind speed, hence, criteria will be discussed in terms of wind speed.

In concluding this section, it is worth re-casting the opening sentence by now saying that it is the peak gust wind speeds and associated gradients which people feel most.

4. Relationships between peak gust and the mean wind speeds

The peak gust wind speed $\hat{u}$ is dependent on turbulence intensity and can be given in terms of the mean $\bar{u}$ and standard deviation σ_u as

$$\hat{u} = \bar{u} + 3.5\,\sigma_u \qquad (1)$$

For example, for a turbulence intensity ($\sigma_u/\bar{u}$) of 15%, $\hat{u} = 1.5\,\bar{u}$, and for 30%, $\hat{u} = 2.0\,\bar{u}$, etc.

As noted, it is the peak gust wind speeds and associated gradients which people feel most and as such it is of interest to know under what conditions they occur. The observations of Melbourne and Joubert [4] indicated that the areas in full scale which have been classed as having unpleasant or unacceptably high wind speeds were all associated with high mean wind speeds. Later, model- and full-scale measurements by Isyumov and Davenport [5] and Melbourne [6] continued to show that the windiest areas were associated with high mean wind speeds, but that the turbulence intensity was important in determining the peak gust wind speeds. In the case of the former, the ratio of peak gust wind speed over mean wind speed $\hat{u}/\bar{u}$ for the three windiest conditions respectively were 1.5, 2.7 and 2.8 and for the latter 1.9, 1.9 and 2.4. For areas and wind directions with lower wind conditions, and obviously for much greater turbulence intensities, this ratio was typically as high as 5.0. This means that to get an accurate prediction of peak gust wind speeds from wind-tunnel model tests, it is essential that mean and rms or peak values for a given probability level be actually measured.

Although it is possible to have unpleasant areas with low mean wind speeds and high turbulence intensities, the evidence to date does seem to indicate that for areas likely to have unacceptably high wind conditions, such as near corners, in narrow alleys and in arcades, the turbulence intensity is relatively low and that in these areas it would be reasonable to assume that the peak gust wind speeds will be about twice the mean wind speed. This means that wind-tunnel investigations, in terms of exploring and improving likely areas of high wind conditions, can often be reasonably based on very simple and inexpensive model measurements of mean wind speed. However, this does not mean that the need to model the turbulence characteristics of the incident wind stream can be overlooked, as a low turbulence stream would produce quite different flow fields and erroneous information.

5. Melbourne's criteria for environmental wind speeds

Notwithstanding the usefulness of the above very simple tests, to maintain flexibility in the application of environmental wind-speed criteria to all levels of turbulence, the author believes it is necessary to frame the definition in terms of gust wind speeds related to some meaningful return period or frequency of occurrence. Criteria which are defined only by mean wind speeds need to be qualified with respect to turbulence to have any general application.

Melbourne's criteria [2, 7] were based on two levels of wind speed, an unacceptable level at which wind gusts would be strong enough to knock people over and a level generally acceptable in main public access-ways based on conditions which had existed in the main Australian cities during the first half of the 20th century, when building was dense but heights restricted to about 30 m. Temperatures are typically between 10° C and 30° C with people appropriately dressed for the outside temperature conditions. These criteria simply state that in main public access-ways wind conditions are

(a) completely unacceptable if the annual maximum gust exceeds 23 m/s (the gust speed at which people begin to get blown over),

(b) generally acceptable if the annual maximum gust does not exceed 16 m/s (which results in half the wind pressure of a 23 m/s gust). Along the lines of Davenport's [8, 9] suggestions for comfort for activities less than walking in a main public access-way, two additional comfort criteria have been added to the original criteria as follows:

(c) generally acceptable for stationary short-exposure activities (window shopping, standing or sitting in plazas), if the annual maximum gust does not exceed 13 m/s,

(d) generally acceptable for stationary, long-exposure activities (outdoor restaurants, theatres), if the annual maximum gust does not exceed 10 m/s.

From these basic criteria a probability distribution, or frequency of occurrence, can be developed to suit any turbulence conditions. An example of such a distribution is given in Fig.1, for a turbulence intensity of 30%, where the distributions of the maximum gust speeds per annum, of 23 m/s, 16 m/s, 13 m/s and 10 m/s are shown as normal distributions back to the maximum hourly mean wind speed per annum (i.e. $\hat{u} = 2.0\,\overline{u}$ for $\sigma_u = 0.3\,\overline{u}$, which as discussed in Section 4 is a very typical situation). The upper part of Fig.1 shows the distribution of hourly mean wind speeds for these conditions using a Rayleigh distribution, and the expected maximum wind speeds for periods of a day, week, month and year have been calculated using a method by Davenport [10].

Davenport showed that the number of storms, on occasions during which a wind speed $\overline{u}$ is exceeded, can be expressed as

$$N_u = \sqrt{2\pi}\,\nu T \left[\Gamma\left(1+\frac{2}{k}\right) - \Gamma^2\left(1+\frac{1}{k}\right)\right]^{1/2} k\,\{-\ln P_{(>\overline{u})}\}^{(k-1)/k}\, P_{(>\overline{u})} \qquad (2)$$

where $P_{(>\overline{u})}$ is the probability of exceeding the mean wind speed $\overline{u}$ (based on the Weibull distribution), k is one of the Weibull parameters, Γ is the Gamma function and νT is the number of independent events per annum. The value of k varies about 1.5 to 2 and νT varies between 500 and 1000, depending on the local wind climate. From an evaluation of Davenport's eq. (2) [5] the ranges given in Table 1 can be obtained which express the relation between probability of exceeding a certain hourly mean wind speed and the number of storms per annum during which that mean wind speed is exceeded. Apart from

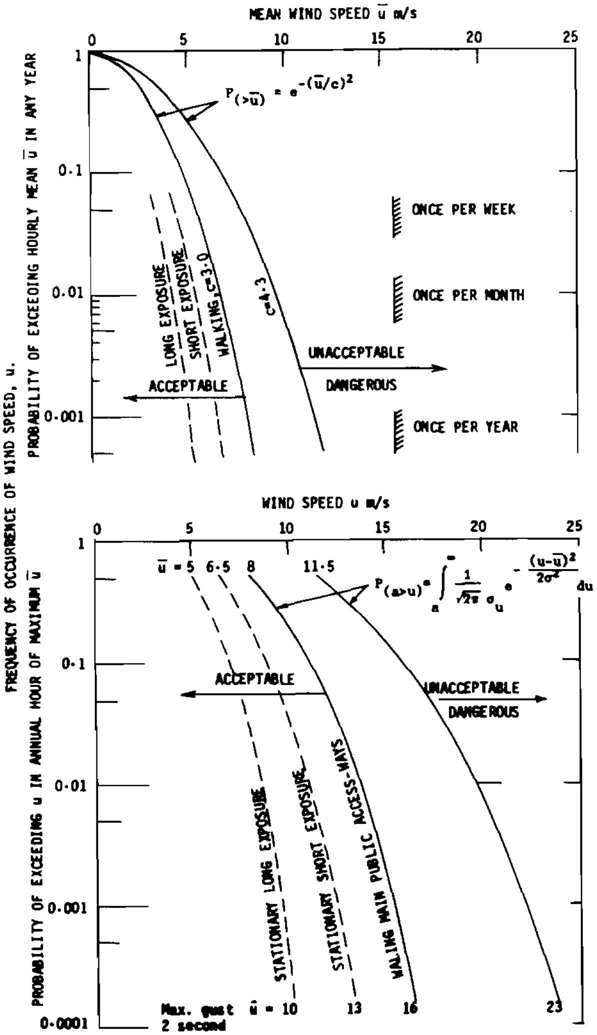

Fig. 1. Probability distributions of Melbourne's criteria for environmental wind conditions for daylight hours, for a turbulence intensity of 30%. $\sigma_u = 0.30\bar{u}$, $\hat{u} = 2.0\bar{u}$.

providing a very important link to give information about the maximum wind speeds likely to occur on average for various periods, such as once per year, once per month, etc., this also provides the necessary link to enable the various environmental wind speed criteria to be compared.

One other complication arises in respect of the number of storms per annum which are relevant to the assessment of environmental wind conditions for human comfort. It is obviously conservative to include winds which blow for all hours of the year, day and night, when most areas under consideration will only be occupied for half of the time or less. Although it does not make

TABLE 1

Relationship between probability of exceeding a mean wind speed and the average number of storms per annum during which that mean wind speed is exceeded

Number of storms per annum during which $\overline{u}$ is exceeded ($N_{\overline{u}}$)	Probability of exceeding an hourly mean wind speed $\overline{u}$ ($P_{(>\overline{u})}$)	
	All hours	Daylight hours
1, once per annum on average	0.00025—0.0005	0.0005—0.001
12, once per month on average	0.003—0.006	0.006—0.012
52, once per week on average	0.015—0.03	0.03—0.06

a great deal of difference, the author prefers to relate criteria and assessment to approximately half the total time, by relating the probability of exceedence to half the yearly cycling rate (i.e. 250—500 independent events per annum) and calling this procedure an assessment of environmental wind conditions relating to "daylight hours"; these ranges are also given in Table 1. Strictly speaking, the cycling rate and evaluation of the wind speed probability distributions should be related to the relevant occupancy times (i.e. daylight hours, afternoon hours, etc.), and in many parts of the world seasonal distributions are also significant. However, for the purposes of this comparison of criteria the simplistic assumptions above described as relating to "daylight hours" will be used in this paper.

6. Comparison of various criteria

Since 1971 several forms of criteria for environmental wind conditions have been published. The criteria developed by Wise [11], Penwarden [12, 13] Davenport [8,9], Lawson [14] and one by Hunt, Poulton and Mumford [3] are given in terms of mean wind speed at some stated or implied level of turbulence intensity between 15% and 20%. Comparison of these criteria can be made in Fig.2 with Melbourne's criteria which have been plotted for a turbulence intensity of 15%, i.e. for $\sigma_u/\overline{u} = 0.15$ and from eqn. (1) $\overline{u} = \hat{u}/1.5$.

Wise [11], in 1971, commented in relation to the Beaufort scale "that wind speeds much above about 5 m/s are likely to give unpleasant disturbance to clothing and hair" and "making reasonable assumptions about metabolic rate, and the thermal resistance of body layers and clothing, speeds of some 5 m/s appeared tolerable at 10° C in normal winter clothing". Penwarden [12] in 1973 and again in collaboration with Wise [13] in 1975 prepared a summary of wind effects on people based on a modified version of the Beaufort Scale from which the following three points can be extracted

discomfort begins $\bar{u}$ = 5 m/s
unpleasant $\bar{u}$ = 8—10 m/s
dangerous $\bar{u}$ = 15—20 m/s.

Penwarden and Wise [13] quoted a criterion which they had used at the Building Research Station, that conditions were regarded as acceptable, or no remedial action was required, if $\bar{u} < 5$ m/s for 80% or more of the time and vice versa, that remedial action would be taken if $\bar{u} > 5$ m/s for more than 20% of the time. In probability terms this criterion is interpreted as being acceptable if $P_{(\bar{u} > 5)} \leqslant 0.2$.

Davenport [8, 9] in 1972 amalgamated work by Wise, Melbourne and Joubert and suggested criteria for a range of activities; these were related to a Beaufort scale for open-country mean wind speeds at 10 m. These criteria also noted that the relative comfort level might be expected to be reduced by one Beaufort number for every 20° C reduction in temperature. In particular Davenport nominated the following hourly mean wind speeds (converted to 2 m) conditions as being tolerable if not exceeded more than once per week, which in probability terms are interpreted as being acceptable for

walking fast	if $P_{(\bar{u} > 10)} \leqslant 0.05$
strolling, skating	if $P_{(\bar{u} > 7\frac{1}{2})} \leqslant 0.05$
standing, sitting, short exposure	if $P_{(\bar{u} > 5\frac{1}{2})} \leqslant 0.05$
standing, sitting, long exposure	if $P_{(\bar{u} > 3\frac{1}{2})} \leqslant 0.05$

Lawson [14] in 1973 used the same Beaufort scale as Penwarden and developed a figure to take into account the effects of turbulence. A value of $\hat{u}$ = 1.7 $\bar{u}$ was used, which from eq. (1) implies a turbulence intensity of about 20%. Lawson quotes Beaufort 4 wind speeds (6—8 m/s) as being tolerable if not exceeded for more than 4% of the time; and Beaufort 6 wind speeds (11—14 m/s) as being unacceptable if exceeded for more than 2% of the time. In probability terms these criteria are interpreted as being

acceptable	if $P_{(\bar{u} > 6-8)} \leqslant 0.04$
unacceptable	if $P_{(\bar{u} > 11-14)} \geqslant 0.02$

Hunt, Poulten and Mumford [3] in 1976 described a range of wind-tunnel tests which were conducted to show how wind affects people's abilities to perform simple tasks, including a simulation of turbulence. Two criteria were developed, firstly that if wind conditions are to be tolerable and for most kinds of performance to be unaffected

$$\bar{u} < 9/(1 + 3 \text{ turbulence intensity})$$

for turbulence intensity of 15% this becomes $\bar{u} < 6.2$ m/s, and secondly, for safe and sure walking that there must be a low probability (say 1%) of a gust lasting over a few paces (say 5—10 m) exceeding 13 m/s. For a turbulence intensity of 15% the 13 m/s gust becomes a mean wind speed of 13/1.5 = 8.7 m/s. (Hunt used a conversion from Durst to give 9 m/s.) In probability terms

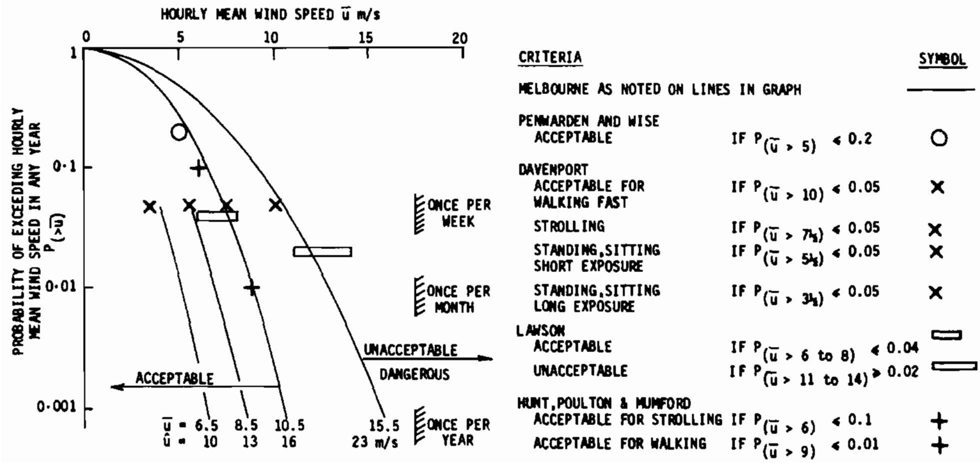

Fig. 2. Comparison of various criteria for environmental wind conditions for daylight hours for a turbulence intensity of 15%. $\sigma_u = 0.15\overline{u}$, $\hat{u} = 1.5\overline{u}$.

for 15% turbulence intensity, this is interpreted as being

acceptable for strolling if $P_{(\overline{u} > 6)} \leqslant 0.1$
acceptable for walking if $P_{(\overline{u} > 9)} \leqslant 0.01$

These criteria in probability terms have been compared in Fig.2 with Melbourne's criteria plotted for a turbulence intensity of 15%.

7. Conclusions

It remains to conclude that the degree of agreement between the criteria when presented in probabilistic terms is quite remarkable for a phenomenon which relies almost completely on subjective assessment. This is particularly so for the earlier attempts by Wise, Melbourne and Penwarden where the criteria were developed entirely independently and in quite different ways. The agreement of the later published criteria, whilst supportive, is not quite so remarkable as there has been a certain amount of influence from the earlier attempts. It seems reasonable to conclude that assessments based on any of these criteria could be said to be made with some consensus of international opinion. However, assessment of the viability of any area in terms of wind environment still relies heavily on the assessment of the use to which the area is to be put and the cost-effectiveness of providing protection from the wind.

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Paper 9

WIND ENVIRONMENT STUDIES IN AUSTRALIA

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Summary

The assessment of prospective environmental wind conditions about proposed building developments in Australia has been discussed. Assessment techniques, making use of wind tunnel studies, have been illustrated with examples from a study of two possible building configurations for a very exposed site on the north side of the City of Melbourne.

A method of predicting the probability of occurrence of a given wind speed at a particular location has been detailed, and examples have been given of the integration of model measurements of local velocities with the wind speed probability distribution for the geographic area. The comparisons of these probabilistic estimates with environmental wind speed criteria have been discussed and illustrated.

A method of measuring peak gust wind speeds at model scale in situations of high turbulence intensity has been given and a comparison is given with a full scale situation.

1. Introduction

An assessment of prospective environmental wind conditions is now carried out for virtually all major building developments in Australia; for several of the major cities it is a mandatory requirement of the licensing authority. Some of the proposed developments become the subject of wind tunnel studies because of their size and particular exposure to strong wind directions, or when the architect wants an evaluation of several possible schemes, or where the development of a particularly well protected recreational area or shopping precinct is required. Because of a steady build-up of experience in architects' offices of how to design to avoid undesirable environmental wind conditions, there has been a significant reduction in the number of wind tunnel studies required and most are now occasioned by an architect or client wanting to create configurations with better than average environmental wind conditions.

Feedback from developments which have been the subject of wind tunnel tests, and some full scale studies, have permitted the development of the criteria discussed by Melbourne [1]. Much of the techniques used in conducting these wind tunnel tests in Australia by Melbourne at Monash University and Vickery at the University of Sydney have been reported in the text Architectural Aerodynamics [2]. This text concentrated more on examples for architects, in particular how environmental wind problems are caused and how they can be avoided. Hence it would seem to be more appropriate in this paper to discuss the probabilistic techniques used in Australia to assess prospective environmental wind conditions about a proposed development from wind tunnel tests. To illustrate these techniques, examples will be drawn from an investigation carried out at Monash University on the relative merits of two possible configurations for a very exposed site on the north side of the City of Melbourne, one proposal was made up of rectangular building towers and the alternative proposal was based on towers with a circular planform.

2. Wind tunnel techniques

As discussed in both Refs. [1] and [2], it is the wind pressures caused by peak gust wind speeds and associated gradients which people feel most. Although it is possible to have unpleasant areas with low mean wind speeds and high turbulence intensities, the evidence to date does seem to indicate that in areas likely to have unacceptably high wind conditions, such as near corners, in narrow alleys and in arcades, the turbulence intensities are relatively low (20 to 30%) and that in these areas it is reasonable to assume that the peak gust wind speeds will be about twice the mean wind speed. In many cases these problems can be assessed adequately through measurements of local mean wind speeds referenced to a probability distribution of wind speeds for the area. Measurements of mean wind speeds can be simply made with either small pitot static tubes or hot wire anemometers. The exception can occur when assessment is required of an area, such as a recreational plaza for long exposure, which is surrounded by buildings. The turbulence intensity in these situations can be high and the criteria for comfort very strict and in these cases it is necessary to measure peak gust wind speed with a hot wire anemometer.

The measurement of mean velocity pressures with a pitot static tube and the measurement of mean wind speeds with a hot wire both have advantages and disadvantages. The hot wire technique has problems in that the measurement of mean and standard deviation in turbulence intensities above 20% become increasingly suspect and eventually meaningless. However, if only peak gust wind speeds without local directional information are required, then the hot wire technique is relatively satisfactory. The peak gust wind speeds can be obtained from an on line probability analysis of the signal from the hot wire equipment. If the equivalent to a 2 to 3 second gust, as measured by a cup or Dines anemometer in full scale is required, the signal must be appropriately filtered and the velocity with a probability of exceedance of about 2×10^{-4} (i.e. 3.5 standard deviations above the mean for a normally distributed process) taken as the equivalent gust wind speed.

For the majority of wind tunnel investigations the author prefers to use the technique of measuring mean velocity pressures with pitot static tubes as shown diagramatically in Fig.1. The mean velocity pressure can be simply

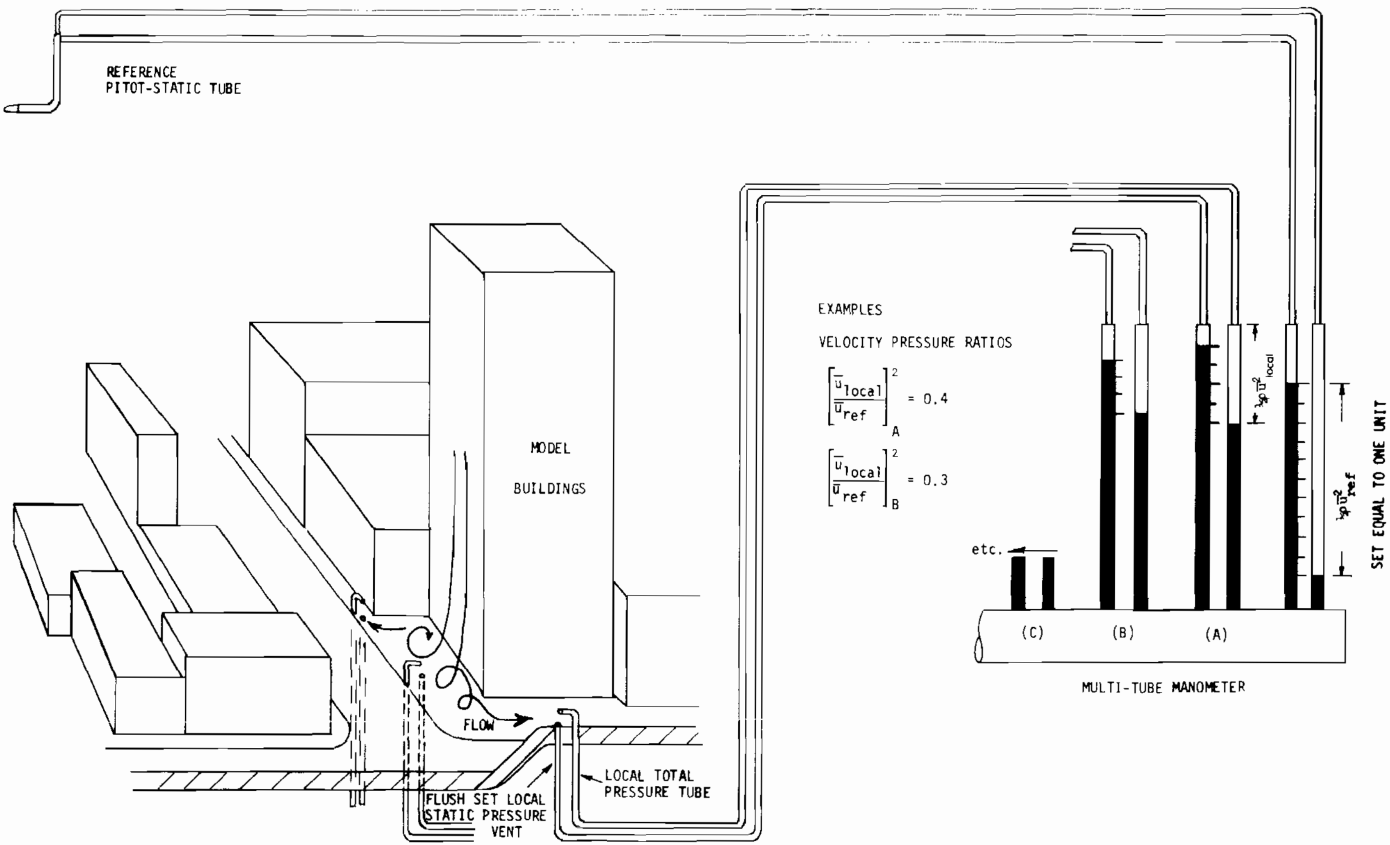

Fig.1. Experimental arrangement for measuring mean velocity pressure ratios.

measured by using a length of small diameter tubing bent in the horizontal plane to measure total pressure in conjunction with a surface static vent. The mean velocity pressures at a number of stations can be measured at the same time by displaying the velocity pressure on a multitube manometer. The disadvantage of this technique is that the total pressure tubes have to be aligned to face directly into wind to get the maximum reading (which does have the benefit of indicating the local wind direction), and peak gust wind speed readings cannot be satisfactorily obtained even if a pressure transducer is used. It is more satisfactory to use a hot wire anemometer to measure peak gust wind speed.

Both techniques require that measured local velocity pressures or wind speeds be referred as a ratio to some reference velocity pressure or wind speed, such as at or near gradient height, which can in turn be related to a full probability distribution of wind speeds for the area. These techniques and probabilistic analysis will be illustrated in the following example.

3. Assessment of prospective environmental wind conditions

The assessment of prospective environmental wind conditions about a proposed development in Australia goes through a series of stages of which the following are typical:

(i) The client and architect discuss broad principles with a number of specialist consultants, one of whom is the wind enginner or aerodynamicist.

(ii) Several configurations or themes on one configuration are developed for the assessment of environmental wind conditions.

(iii) A probability distribution of wind speeds with direction, relative to the site, is compiled.

(iv) Wind tunnel tests are made on the various configurations and modifications developed at the time the models are in the wind tunnel.

(v) The wind tunnel data are integrated with the wind speed data to facilitate a final assessment of the environmental wind conditions.

In practice, the integration of the wind tunnel and wind speed data is done continuously throughout the wind tunnel test programme, to facilitate continuous assessment and decisions by the client and architect to dictate the direction of the test programme. The author will only conduct wind tunnel tests of this type when senior client and architect representation at the wind tunnel can be guaranteed. There are some very simple ways in which the wind tunnel data can be assessed with respect to the wind speed data and these will be illustrated in the following example.

3.1 Example of wind tunnel testing and initial assessment procedure

The example chosen is that of a major development proposal to be located on the northern edge of the Central Business District of the City of Melbourne. The architects were particularly aware of the fact that such a development would be exposed to the wind directions from which come the strongest and most frequent winds. Similarly, they were aware that there was little likelihood of any significant shielding being developed for these directions in the fore-seeable future. Accordingly, they developed two proposals for assessment of environmental wind conditions. The first was based on three rectangular tower buildings with extensive canopy arrangements near ground level and the second was based on three circular towers of similar size and arrangement with the ground level area left completely open. Photographs of these two models are shown in Fig.2.

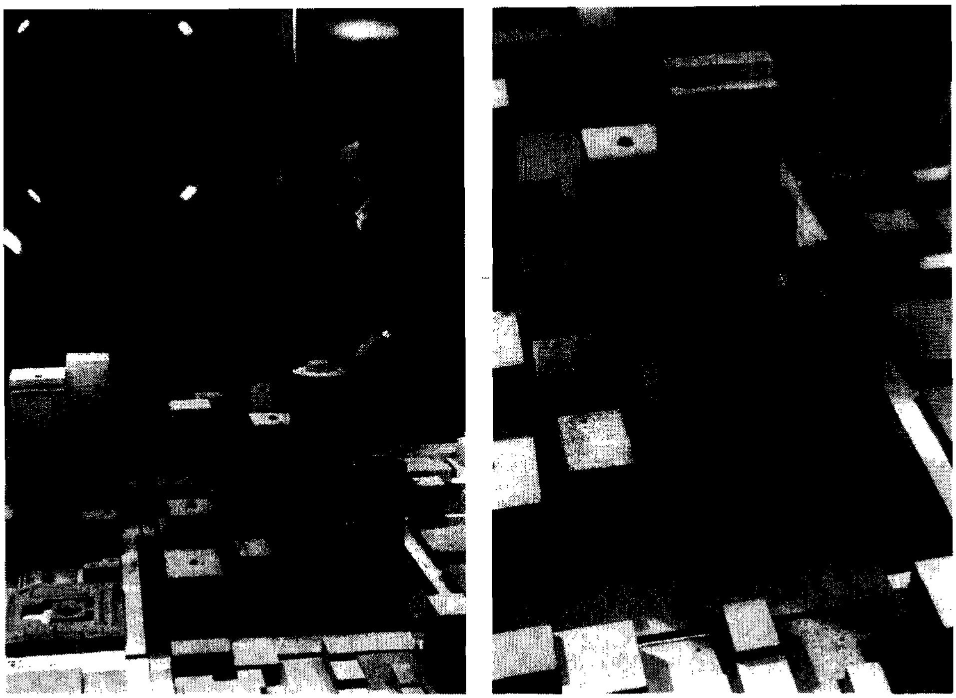

Fig.2. 1/400 scale models of a development proposed for the City of Melbourne.

Before the commencement of the wind tunnel test, it is necessary to prepare a probability distribution of wind speeds. An example of such a distribution is given in the first part of Table 1 in the form of the raw data as were obtained from records of measurements made with a Dines anemometer located at a height of 10 m at Essendon Airport some 10 km north of the City of Melbourne. The cumulative probability distribution for each of the 16 wind directions (θ) can be fitted to a Weibull distribution, which takes the form,

$$P_{(>\overline{u})\theta} = A_\theta \exp-(\overline{u}/c_\theta)^{k_\theta} \qquad (1)$$

which then can be presented in a polar plot with lines of constant probability

TABLE 1

Probability distribution of hourly mean wind speeds measured at 10 m height in open country terrain at Essendon Airport, Melbourne, Australia, 1959—71 for daylight hours 0730 to 1930, and environmental wind criteria per 22½° sector

	Band of wind speeds, $\overline{u}$ (m/s)					
$\overline{u}$ at 10 m over open country terrain	0.5 to 2.1	2.1 to 3.6	3.6 to 5.65	5.65 to 8.75	8.75 to 11.3	11.3 to 14.4
$\overline{u}$ at 300 m over suburban terrain*	0.8 to 3.2	3.2 to 5.5	5.5 to 8.6	8.6 to 13.4	13.4 to 17.3	17.3 to 22.0
Wind direction	Probability of being in band × 10^6					
N	11973	15323	37400	64368	31085	15543
NNE	3900	4340	8238	12468	4943	2800
NE	6535	3185	2855	1538	440	110
ENE	5218	1813	660	165	55	
E	7800	2800	1098	330		
ESE	4340	2690	2088	1318	330	
SE	9008	7745	9720	7635	1593	440
SSE	8733	11698	16423	12138	933	165
S	18948	32898	64753	68543	9063	933
SSW	9338	10490	18180	17630	3680	1043
SW	11080	12633	20485	18508	6205	2418
WSW	5823	6700	11588	14280	5548	2965
W	9555	11040	7963	21968	7690	2528
WNW	4558	5273	7963	7360	1703	715
NW	6480	7853	10215	12578	7223	1868
NNW	5878	8073	12633	17025	7280	2418
Calm	88788					
Total	1000000					

$^*\overline{u}_{300,\text{ suburban}} = \overline{u}_{10,\text{ open country}} \left[\frac{400}{10}\right]^{0.15} \left[\frac{300}{500}\right]^{0.25} = 1.53\,\overline{u}_{10,\text{ open country}}$.

**For a lower turbulence intensity of $\sigma_u = 0.15\overline{u}$, $\hat{u} = 1.5\overline{u}$, the numerical criteria become Unacceptable/dangerous, annual maximum $\overline{u} > 15.5$; Acceptable/walking, annual maximum $\overline{u} < 10.5$.

		Average annual hourly maximum wind speed at 300 m for each sector from line with $P_{(>\bar{u})} = 0.001$ in Fig.3	Environmental wind criteria based on Melbourne's criteria for $\sigma_u = 0.3\bar{u}$, $\hat{u} = 2.0\bar{u}$**			
14.4 to 17.5	17.5 to 21.1		Unacceptable/ dangerous annual maximum $\bar{u} > 11.5$ m/s		Acceptable for walking annual maximum $\bar{u} < 8.0$ m/s	
22.0 to 26.7	26.7 to 32.3		For $\bar{u}_{local} = 11.5$		For $\bar{u}_{local} = 8.0$	
			$\frac{\bar{u}_{local}}{\bar{u}_{300}}$	$\left[\frac{\bar{u}_{local}}{\bar{u}_{300}}\right]^2$	$\frac{\bar{u}_{local}}{\bar{u}_{300}}$	$\left[\frac{\bar{u}_{local}}{\bar{u}_{300}}\right]^2$
2910	275	24	0.48	0.23	0.33	0.11
330		20	0.58	0.33	0.40	0.16
		12	0.96	0.91	0.67	0.44
		6	1.9	3.7	1.3	1.8
		6	1.9	3.7	1.3	1.8
		10	1.2	1.3	0.8	0.64
		14	0.82	0.67	0.57	0.33
		14	0.82	0.67	0.57	0.33
55		18	0.64	0.41	0.44	0.20
110		17	0.68	0.46	0.47	0.22
165		19	0.61	0.37	0.42	0.18
605	55	20	0.58	0.33	0.40	0.16
440		20	0.58	0.33	0.40	0.16
165		18	0.64	0.41	0.44	0.20
165	55	19	0.61	0.37	0.42	0.18
330		20	0.58	0.33	0.40	0.16

level as shown in Fig. 3. In this particular plot the mean hourly wind speed has been factored to refer to a height of 300 m over suburban terrain by the relationship,

$$\bar{u}_{300,\,\text{suburban}} = \bar{u}_{10,\,\text{open country}} \left[\frac{400}{10}\right]^{0.15} \left[\frac{300}{500}\right]^{0.25}$$

$$= 1.53\,\bar{u}_{10,\,\text{open country}} \tag{2}$$

In the wind tunnel model tests, the local velocity pressures, or local wind

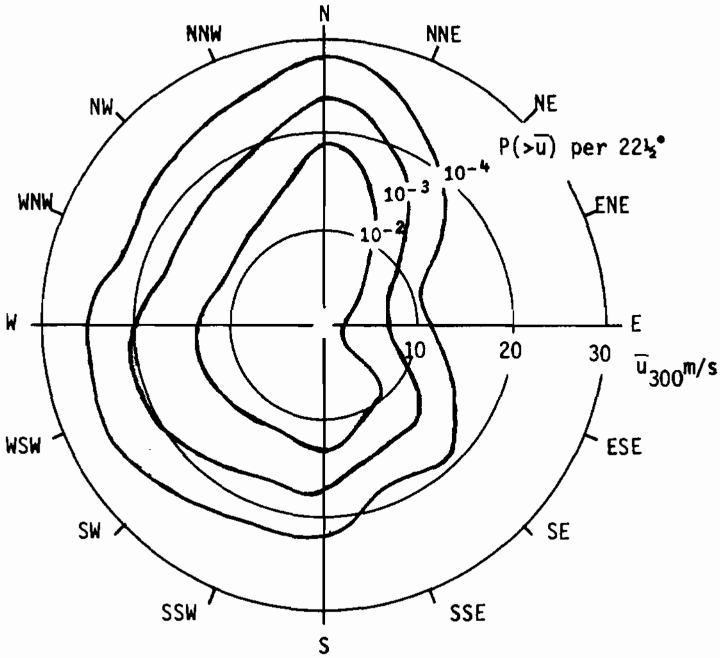

Fig. 3. Probability distribution of hourly mean wind speeds at 300 m over suburban roughness at Essendon Airport Melbourne for daylight hours 0730 to 1930.

speeds, will be measured as a ratio with the similar measurement at 300 m over the model suburban approaches. Hence, if the annual maximum hourly wind speeds at 300 m can be obtained for each wind direction sector, then Melbourne's criteria [1] can be expressed for each sector as a ratio against which any measurements can be directly compared at the time of measurement. The annual maximum hourly wind speed for each sector can be obtained using the probabilities given in [1] and in this case, where the distribution is for daylight hours, the average maximum hourly wind speed can be approximated by reading around the contour with a probability $P_{(>\bar{u})} = 10^{-3}$ in Fig.3 as tabulated in Table 1. With this information the criteria, in ratio form, can be calculated as shown in the last part of Table 1 for the most general case of the peak gust wind speed equal to twice the hourly mean wind speed ($\hat{u} = 2\bar{u}$) for two levels as defined in [1] as being

(a) unacceptable/dangerous if the annual maximum gust wind speed, $\hat{u} > 23$ m/s;

(b) acceptable/for walking if the annual maximum gust wind speed, $\hat{u} < 16$ m/s.

The curves of these two criteria can then be plotted as background information on the data sheets on which the wind tunnel measurements are directly recorded as shown in Fig.4. Obviously this information forms the background for any test series and once it has been obtained for an area, it serves for tests

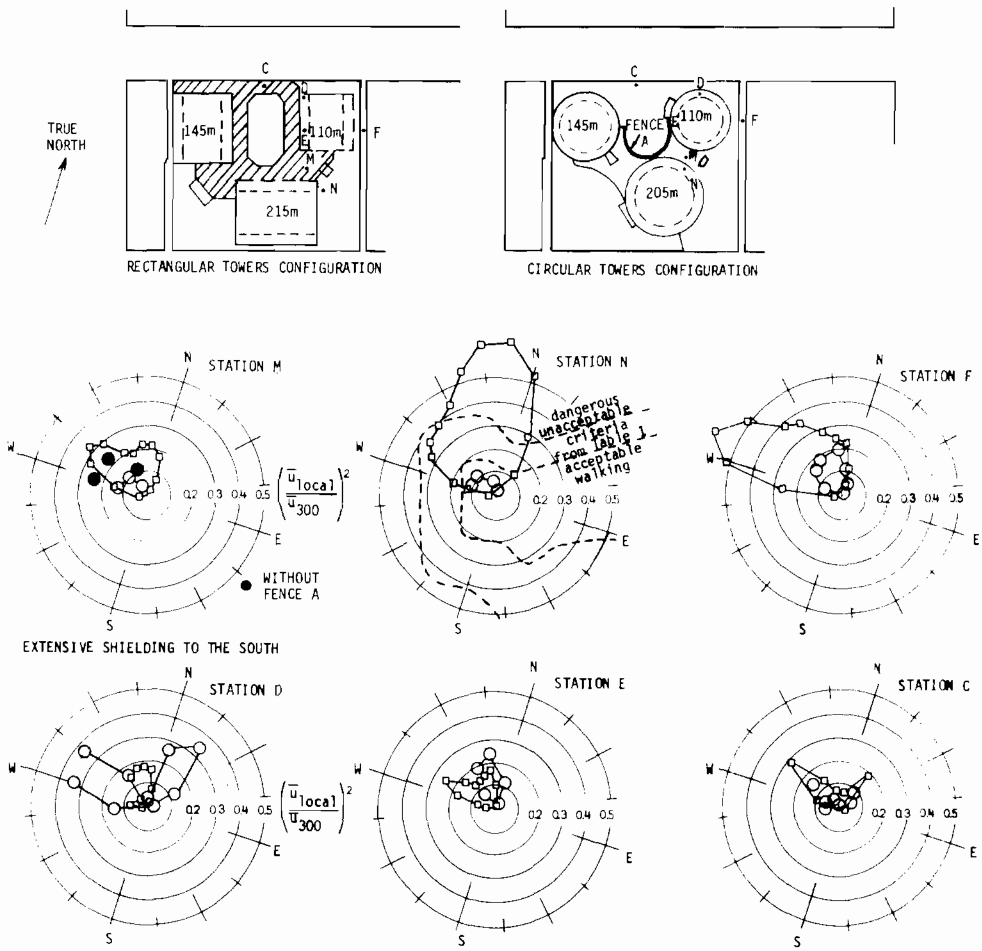

Fig. 4. Mean velocity pressure ratios from wind tunnel model tests.

on all projects in that area. In this particular case, some small modification has to be made to reduce the effect of topographical funnelling which peaks the distribution for northerly wind directions at Essendon Airport, but the effect of which reduces further south over the downtown area of the City of Melbourne and southern suburbs.

Examples of polar plots of velocity pressure ratio as a function of wind direction are given in Fig.4, for 6 of about 30 stations, at which measurements were made to facilitate the assessment of environmental wind conditions for these two configurations. At Stations M, N and F, the very adverse effects of the rectangular buildings inducing flow down to ground level is shown to result in quite unacceptably high velocity pressure ratios (for this geographic region) in critical points of public access. These adverse effects can be offset to some extent by the use of local wind break fences or overcome completely by providing air locked connections under the canopy between the main towers at ground level. The circular tower configuration is shown to induce much less wind flow at ground level and to provide conditions within the "acceptable criterion" at Stations M and N. However, in the absence of surrounding buildings over 30 m height to the north and west, there is still a need for the local protection provided by the 50% porous Fence A shown in Fig.1 and 4. Similarly, wind conditions at Stations D, E and C, for the completely open circular tower configuration, are shown to border on unacceptable levels (and certainly are well in excess of acceptable levels). These very local conditions can be ameliorated with the use of porous wind breaks (planter boxes of shrubs and trees) or by the planned layout of architectural features and main access-ways which keep pedestrian traffic away from local regions where high wind speeds are likely to occur.

In concluding this example of how, during wind tunnel testing, a very quick assessment can be made of prospective environmental wind conditions for various configurations, a word of caution must be made in respect of interpreting the measurements.

First of all, the criteria shown in Fig.4 are for each 22½ degree sector; that is if the velocity pressure ratio (or wind speed ratio, whichever approach is being used) reaches, for example, the criterion for unacceptable/dangerous conditions for one sector, it means that once per annum, on average, the peak gust wind speed of 23 m/s will be exceeded. If the criterion is reached for two sectors, it means the probability of exceeding the criterion will double and so on. To make a proper assessment of the probability of exceeding certain wind speeds for all wind directions, a full analysis for all wind directions must be compiled, as shown in Section 3.2.

Secondly, an assessment has to be made by the experimenter as to when the local turbulence intensity reaches a level which invalidates the use of mean velocity pressures or mean wind speeds, whichever technique is being used. If this stage is reached, the simple technique of relying on mean measurements has to be abandoned and the more sophisticated technique of measuring peak gust wind speeds has to be used. A further word of warning here is that it is not sufficient to rely on mean and standard deviation readings from a hot wire anemometer to indicate when a turbulence level of say 25% is reached, because the errors inherent in the hot wire tend to increase the mean and reduce the standard deviation, hence lulling the unwary into thinking that the turbulence intensity is not all that high. A much safer way to determine whether high turbulence, low mean velocity conditions are present, is to observe the signal on a cathode ray oscilloscope and run out a probability distribution to check on the peak values. One consolation, in a sense, of relying on mean wind speeds measured with a hot wire anemometer to higher turbulence intensities is that the mean wind speeds measured are high, and in most cases excessively conservative decisions are more likely to be made on the basis of this incorrect information. An example of the measurement of peak gust wind speeds will be given in Section 3.3.

3.2 Probability distributions of wind speed for all wind directions

In the majority of situations, high wind speeds induced at a particular station are confined to a relatively narrow band of wind directions and an assessment can be made on the basis of criteria for a given sector as described in Section 3.1. For situations where either a more accurate assessment is required (perhaps for a marginal situation), or high wind speeds occur for a broad range of wind directions, it becomes necessary to prepare a full probability distribution of wind speeds which accounts for all, or all the significant, wind directions. Such a distribution can be prepared as follows:

(a) From a distribution such as given in Table 1, a cumulative probability distribution of wind speeds at the reference point (in this case 300 m over suburban terrain) can be prepared which expresses the probability of exceeding a given wind speed for a given wind direction sector, $P_{(>\bar{u})\,\theta,\,\text{reference}}$. One convenient method of doing this is to use the Weibull distribution noted previously.

(b) For each station an average value of the wind speed ratio, $\bar{u}_{\text{local}}/\bar{u}_{\text{ref.}}$ can be obtained from the model tests for each wind direction sector. Using this wind speed ratio, the cumulative probability distribution can be prepared expressing the probability of exceeding a given wind speed for a given wind direction sector at the local station, $P_{(>\bar{u})\theta,\,\text{local}}$.

(c) The value of $P_{(>\bar{u})\,\theta,\,\text{local}}$ must be obtained for all or all significant wind directions and integrated to give the total probability of exceeding a given mean wind speed for all directions, i.e.

$$P_{(>\bar{u})\,\text{all directions, local}} = \int_{0}^{360} P_{(>\bar{u})\,\theta,\,\text{local}}\, d\theta \tag{4}$$

(d) The whole process can be done conveniently with a digital computer, but it is not a particularly long task to do it manually for a few stations, simply because if the relatively coarse 22½° sectors are used, it is very unusual in practice to have to do the integration of more than three or four sectors. An example of the final stages of this process is given in Table 2 for Station M of the previous example.

(e) Finally, a graph of the probability of exceeding a given wind speed can be superimposed on criteria expressed in the same probabilistic form such as given in [1] and an example of which is given in Fig.5, for several of the stations from the previous example. Whilst such a presentation confirms just how unacceptable conditions would be at Stations M and N for the Rectangular Towers proposal, it is more useful in quantitatively indicating how acceptable the conditions at Station C are likely to be, which can only be very generally assessed from observing the information in Fig.4.

3.3. Measurement of peak gust wind speeds

If, as described in Section 3.1, it is deemed necessary to make an assessment of an area subjected to wind flows with high turbulence intensities, a

TABLE 2

Example of last part of the development of the probability distribution of mean wind speeds at Station M, Rectangular Towers Configuration (Fig.4)

Wind direction	$\overline{u}_{local}$ (m/s)	4	6	8	10	12
	$\frac{\overline{u}}{\overline{u}_{300}}$ frim Fig.4	Probability of being greater than $\overline{u}$ for 22½° sectors of wind direction $P_{(>\overline{u})\theta} \times 10^6$				
N	0.42	80,000	45,000	11,000	1,300	100
NNW	0.47	20,000	12,000	3,000	500	50
NW	0.47	20,000	12,000	3,000	500	50
WNW	0.57	13,000	6,000	2,000	600	150
W	0.40	18,000	7,000	1,000	50	
All other wind directions	< 0.2	Not significant				
Total $P_{(>\overline{u})}$ *		0.15	0.082	0.020	0.0029	0.00035

*These values are plotted in Fig.5.

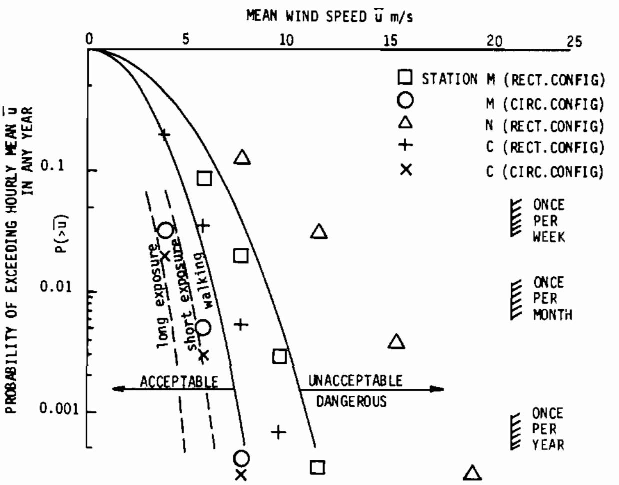

Fig.5. Probability distributions of mean wind speeds at several stations compared with Melbourne's criteria for environmental wind conditions (Daylight hours, $\sigma_u = 0.3\overline{u}$, $\hat{u} = 2\overline{u}$).

measurement of the peak gust wind speeds can be made using a hot wire anemometer as follows:

(a) If it is required to compare model scale peak wind speed measurements with criteria [1] based on peak gusts measured over two to three seconds in full scale, it is first necessary to low-pass filter the hot wire anemometer linearised output, so that it looks like the scaled down version of the output from a typical cup or Dines anemometer.

(b) The next step in the process is to obtain a probability distribution of the filtered hot wire anemometer signal; this can be conveniently obtained using on-line digital analysis techniques.

(c) It is then necessary to determine the probability level equivalent to 2—3 second peak gust in full scale. Many observers of wind data collected from cup or Dines anemometers in open country situations have observed that the peak gust wind speeds are between 1.5 and 1.8 times the mean, and from a knowledge of the turbulence intensities in these situations, it is possible to deduce that the 2—3 second mean wind gust wind speed is approximately 3.5 standard deviations above the mean, i.e.

$$\hat{u}_{2-3\,\text{sec}} = \bar{u} + 3.5\,\sigma_u \tag{4}$$

For a normally distributed process, the probability of exceeding 3.5 standard deviations above the mean is 2.3×10^{-4}. It is suggested that the value of the velocity with a probability of exceedance of 2.3×10^{-4} is an appropriate approximation to use as being equivalent to a 2—3 second mean maximum gust wind speed.

(d) The gust wind speed so obtained can then be expressed as a ratio with the reference mean wind speed and compared with the environmental wind criteria as previously outlined.

The measurement of peak gust wind speeds can be illustrated by the following comparison of a full scale measurement at a city corner, at an intersection near, but not directly adjacent, to tall buildings, and a model measurement for the same situation. The model measurements were made using a hot wire anemometer and the procedure as outlined above.

		Full scale	Model scale
local peak gust wind speed / local mean wind speed,	$\frac{\hat{u}}{\bar{u}}$	4.1	1.8
local mean wind speed / reference mean wind speed,	$\frac{\bar{u}}{\bar{u}_{300}}$	0.21	0.50
local peak gust wind speed / reference mean wind speed,	$\frac{\hat{u}}{\bar{u}_{300}}$	0.8	0.9

It can be seen that the model measurement of the mean wind speed is a very significant overestimate and on its own would be quite misleading. The reason is apparent when one observes that the ratio of local peak to mean wind speed is over four, indicating very high turbulence, and which the hot wire anemometer records at less than two. However, when only the peak gust wind speed is used from a hot wire anemometer in this situation, the comparison between peak and reference mean wind speed ratios compares relatively well.

4. Conclusions

The assessment of prospective environmental wind conditions about a typical proposed building development in Australia has been discussed. Measurement techniques have been described and illustrated with examples. In particular, examples of the probabilistic assessment of local wind speeds and comparison with environmental wind speed criteria have been given in detail. A method of measuring peak gust wind speeds in situations of high turbulence intensity has been given.

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