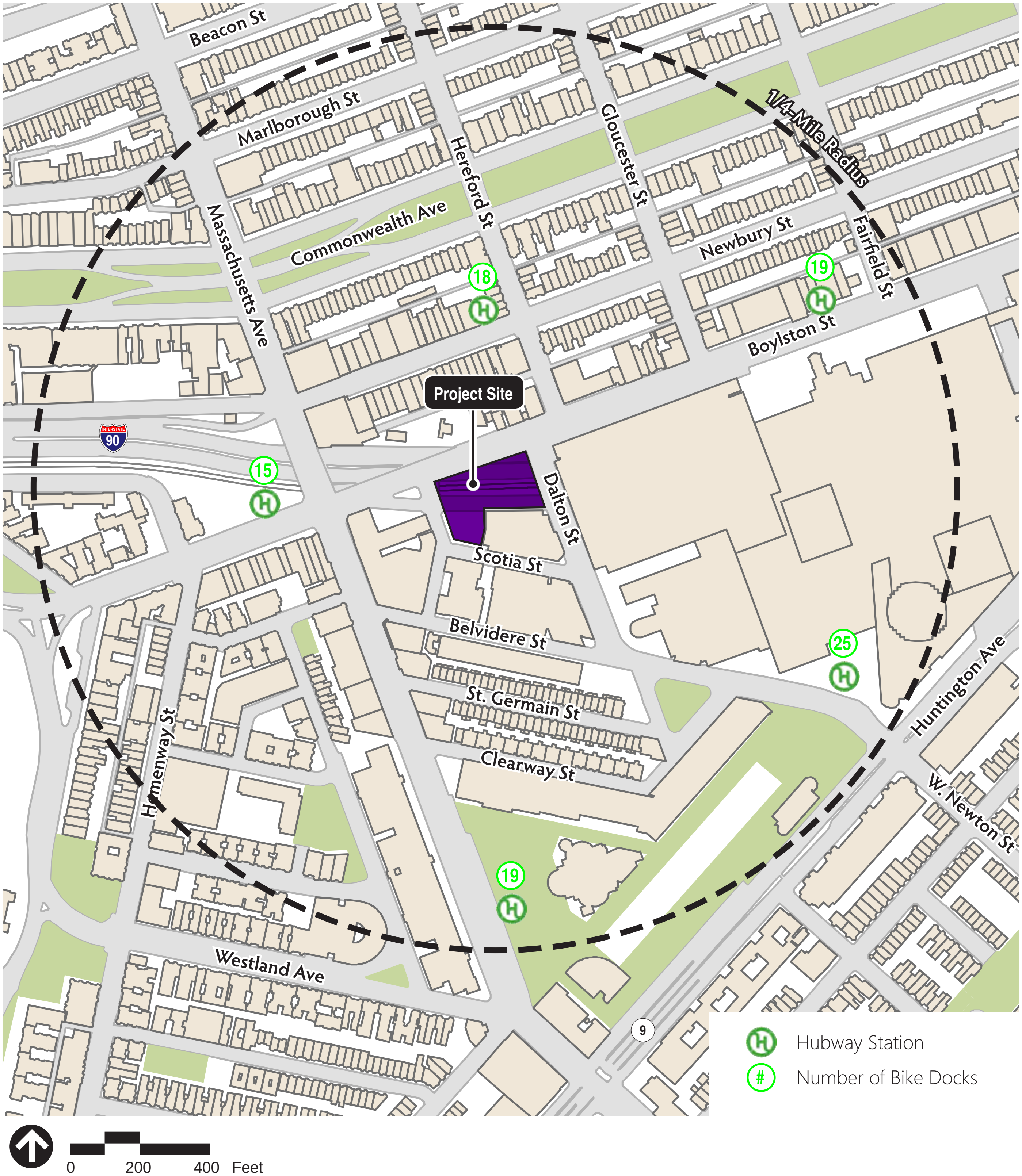
CAC MEETING

October 24, 2017

1000
Boylston Street

W WEINER VENTURES
REAL ESTATE DEVELOPMENT & INVESTMENT

ELKUS | MANFREDI
ARCHITECTS

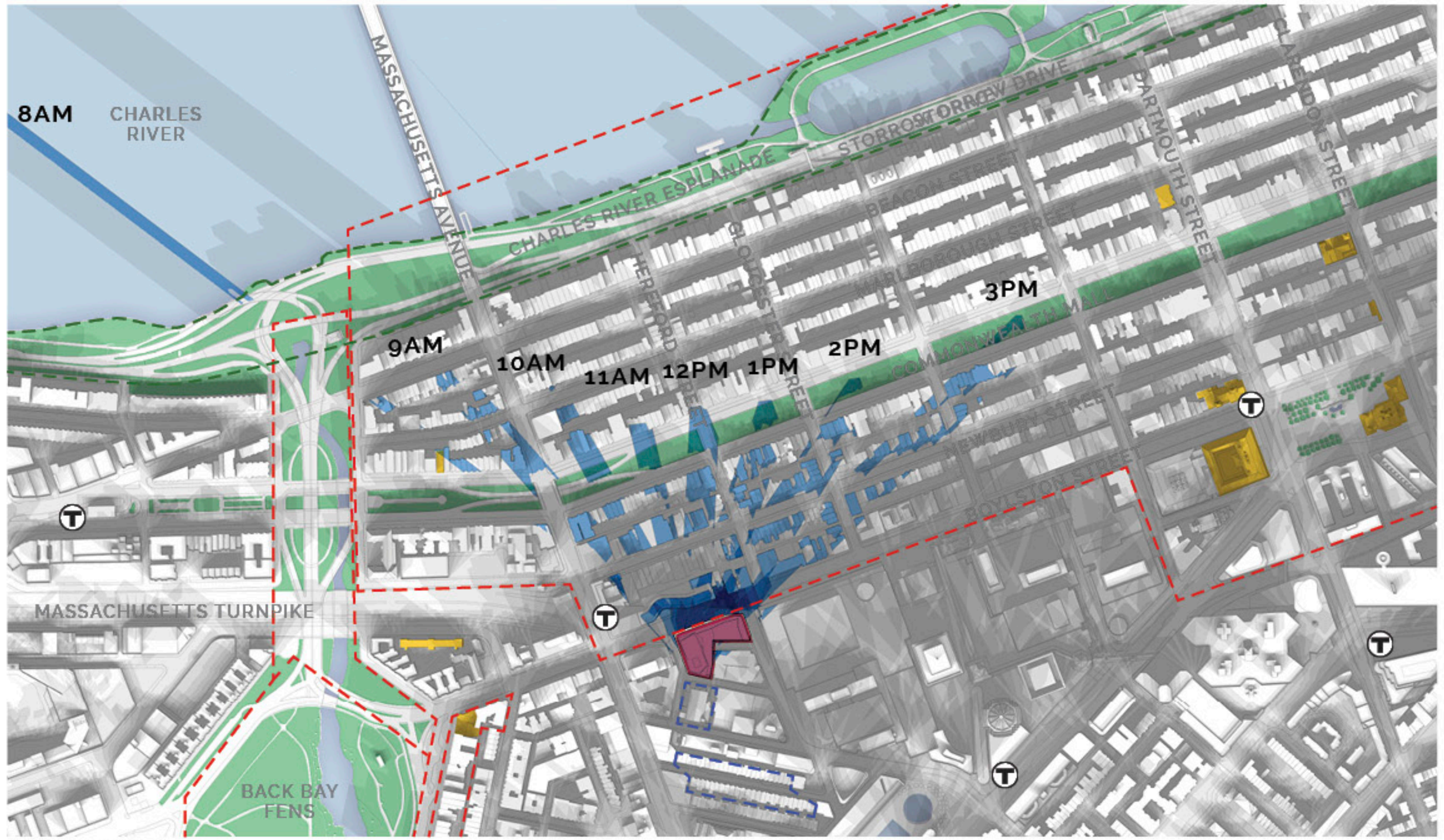


Source: BWSC Street Map

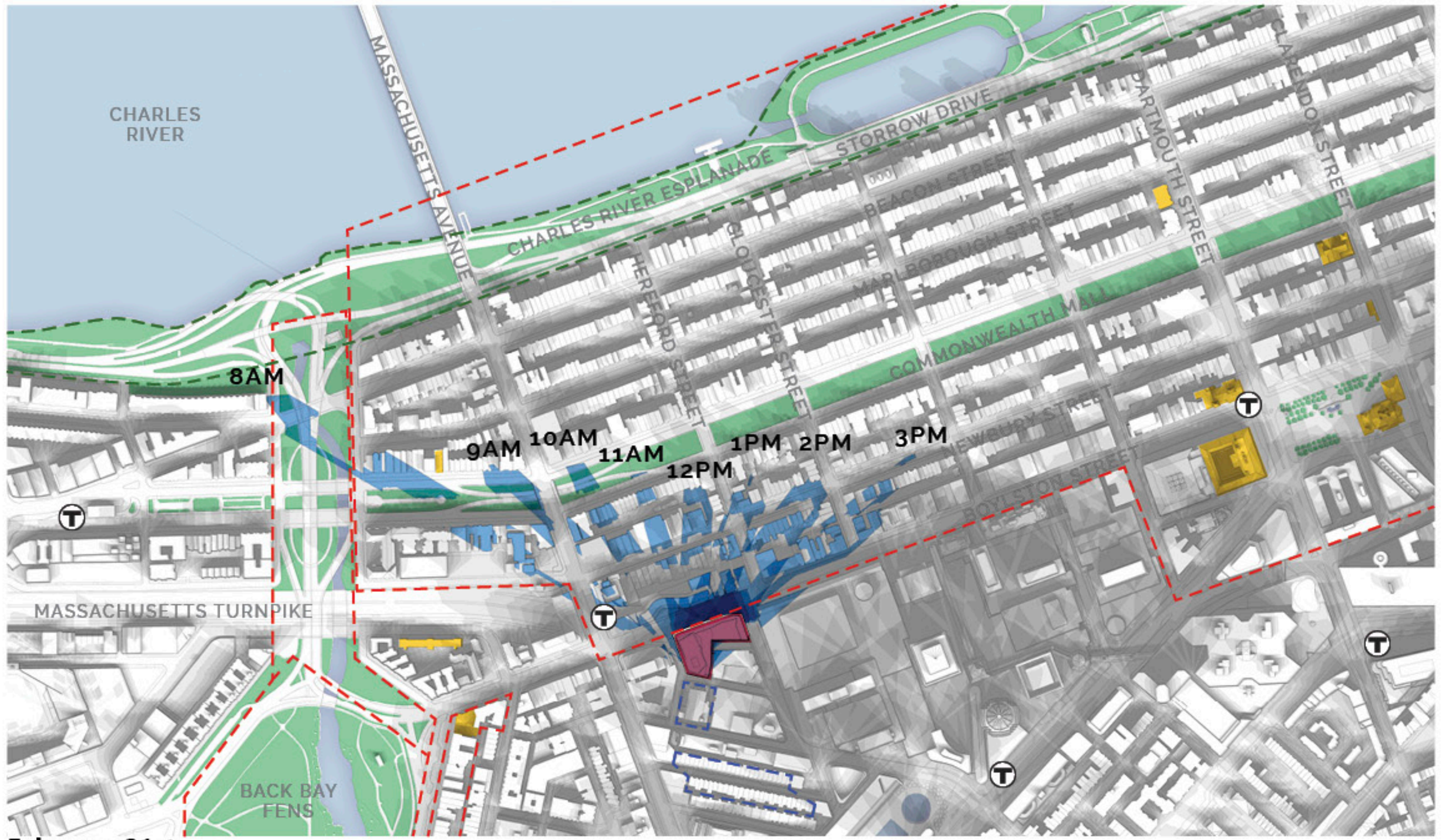
Figure 5.5

Hubway Facilities

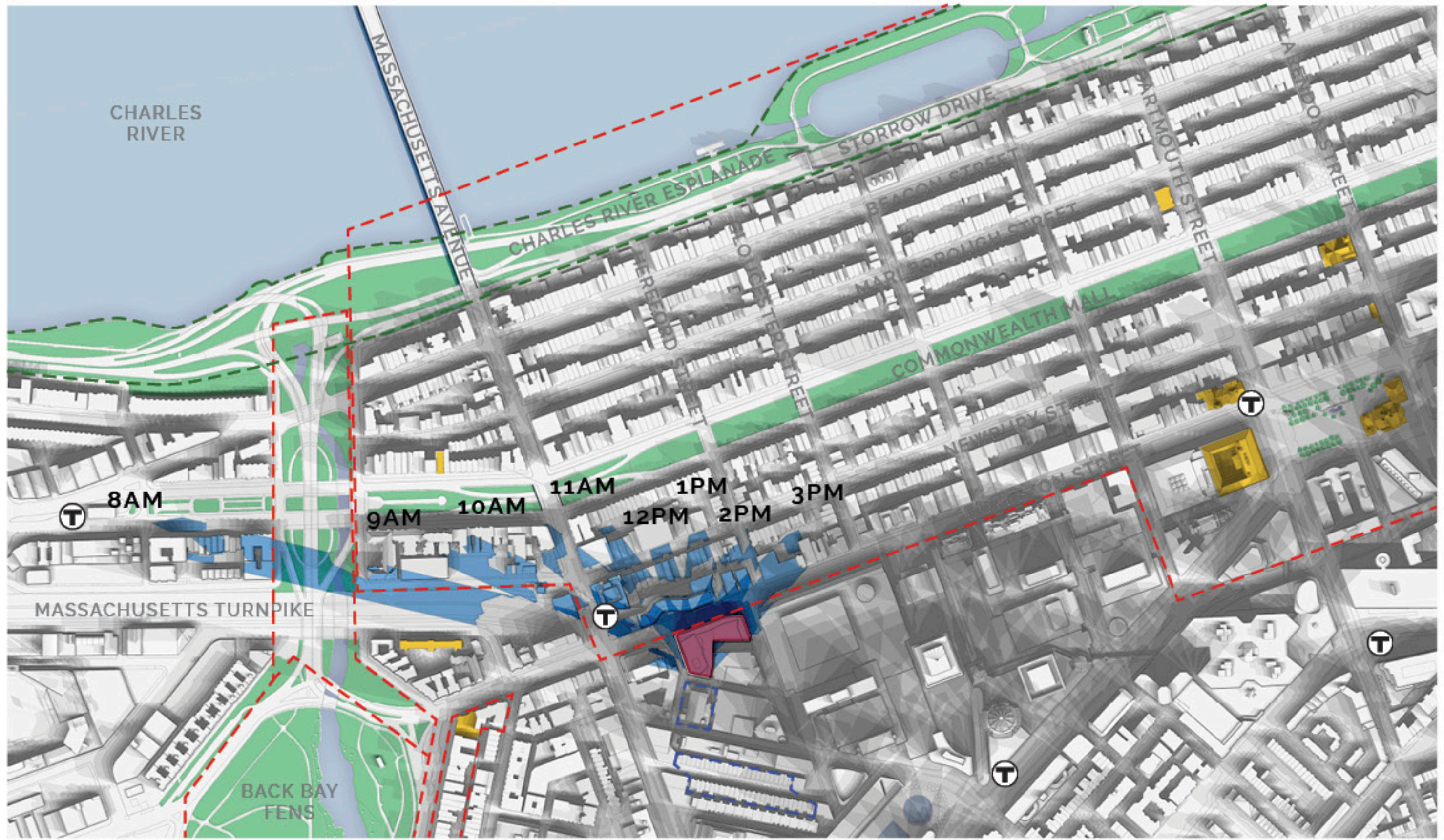
1000 Boylston Street
Boston, Massachusetts



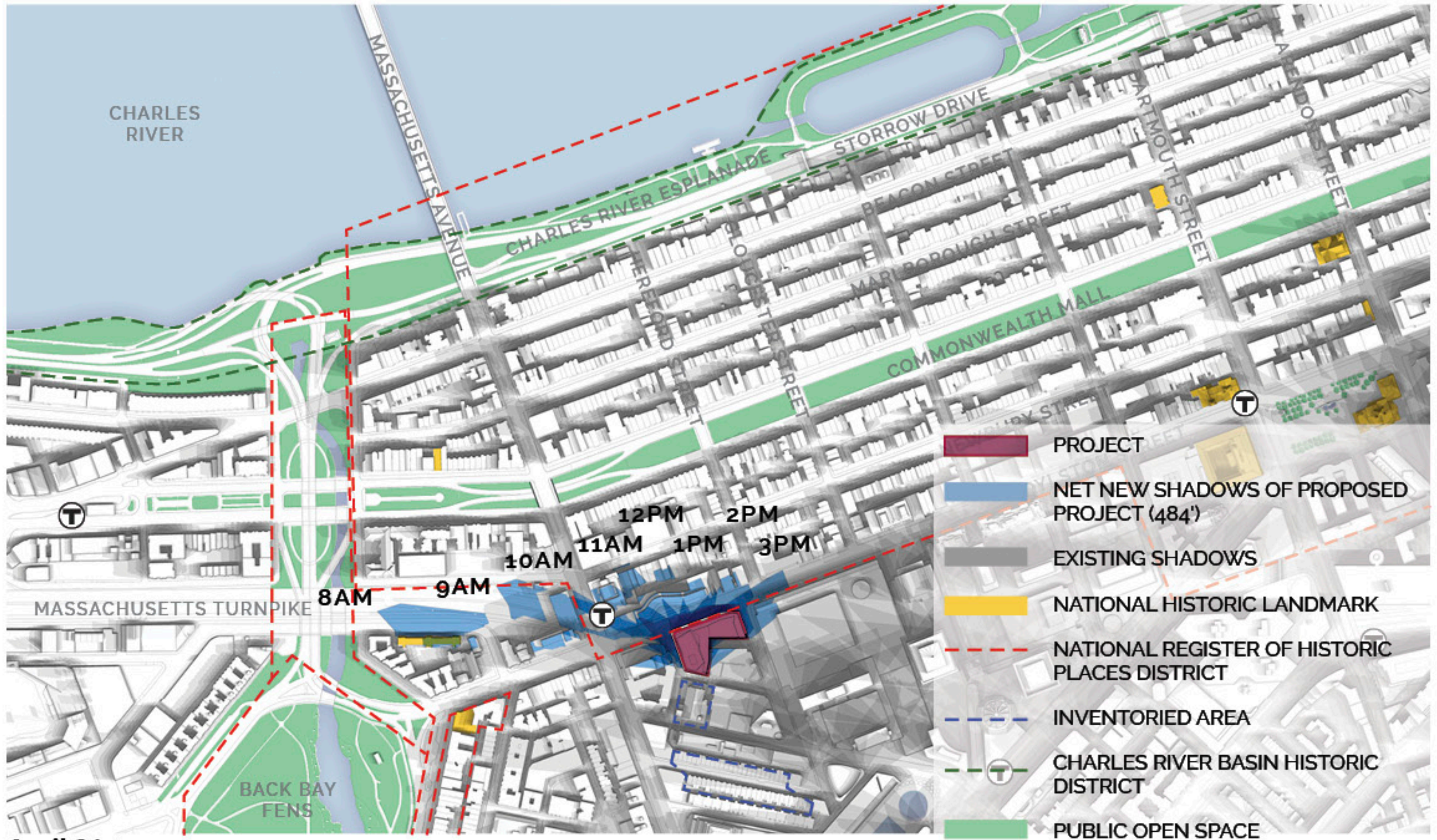
January 21st



February 21st



March 21st



🟥 PROJECT
🟦 NET NEW SHADOWS OF PROPOSED PROJECT (484')
⬛ EXISTING SHADOWS
🟨 NATIONAL HISTORIC LANDMARK
- - - NATIONAL REGISTER OF HISTORIC PLACES DISTRICT
- - - INVENTORIED AREA
- - - CHARLES RIVER BASIN HISTORIC DISTRICT
🟩 PUBLIC OPEN SPACE

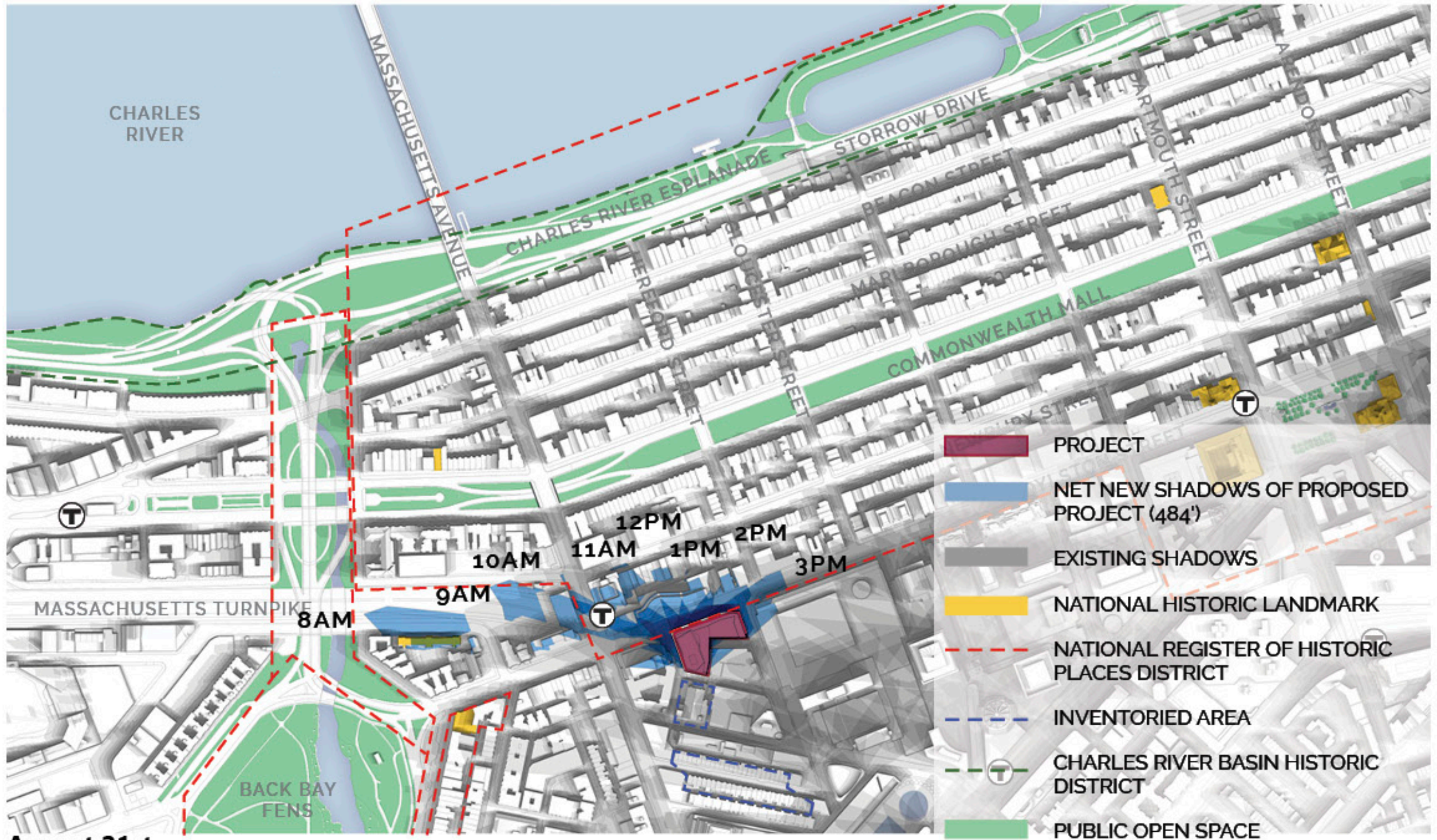
April 21st

SHADOW OVERLAP - JANUARY 21 -APRIL 21

May 21st

June 21st

July 21st



August 21st

1000 BOYLSTON STREET
BOSTON, MASSACHUSETTS

SHADOW OVERLAP - MAY 21 -AUGUST 21

0 400' 800' N

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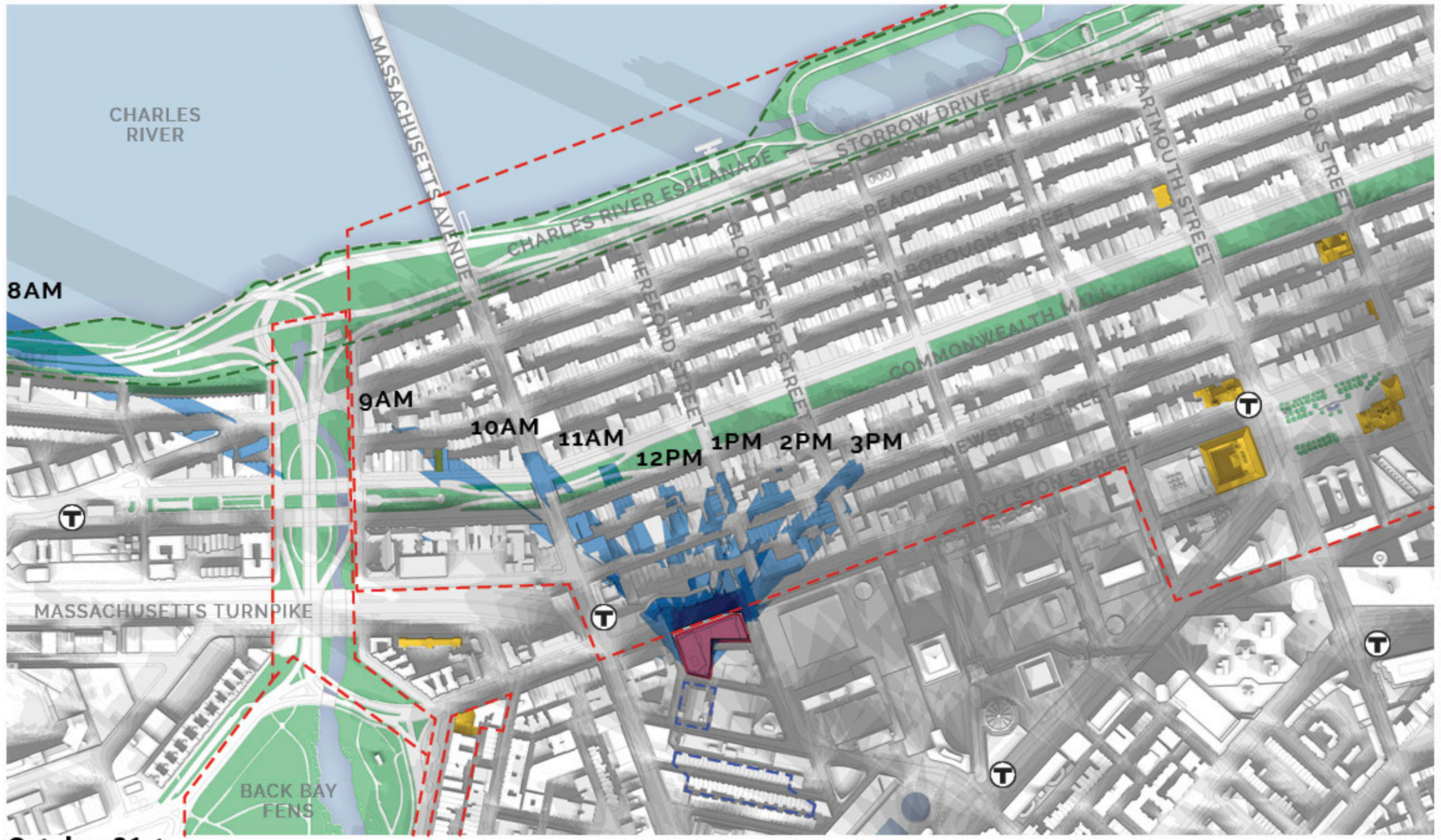
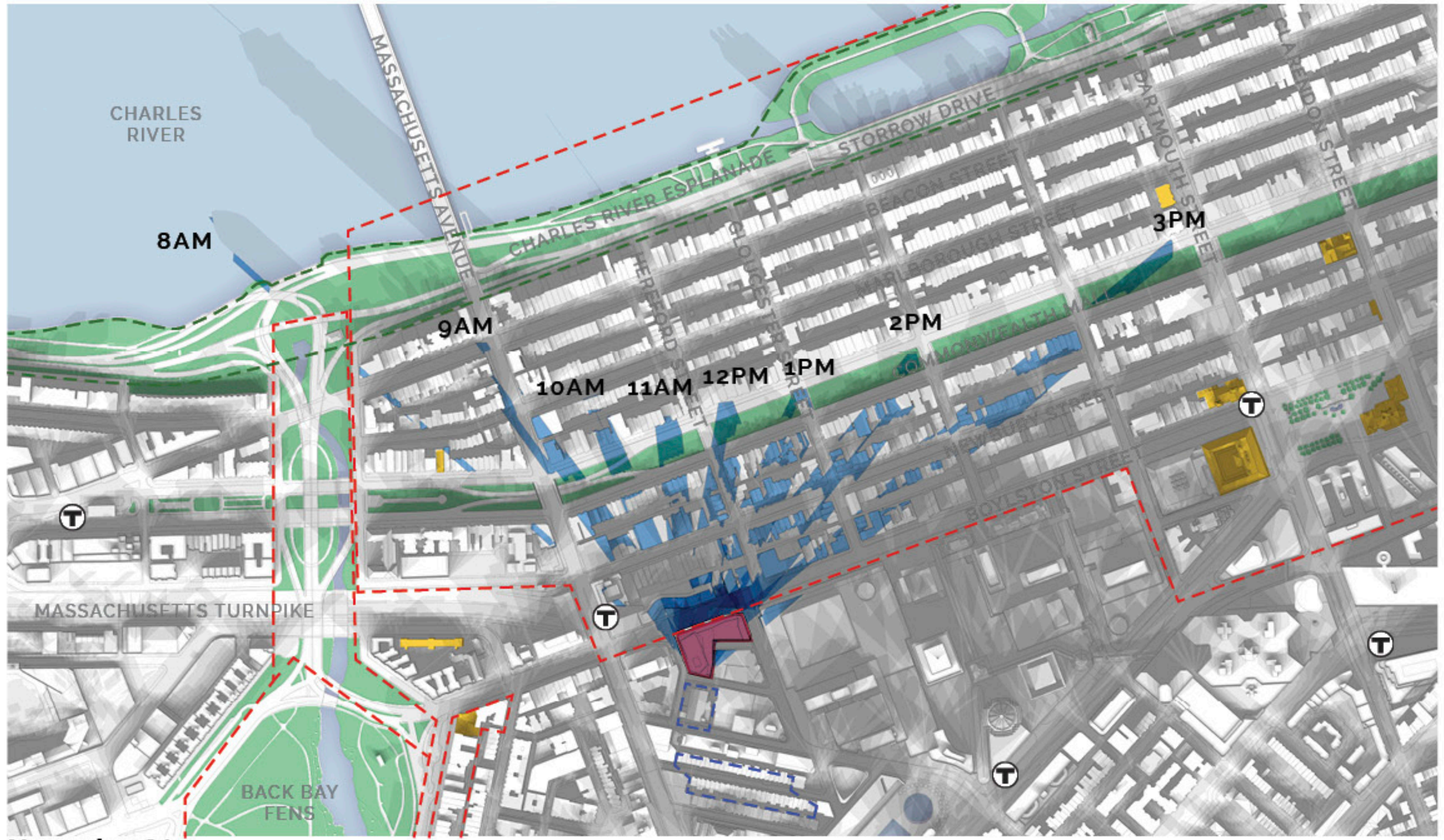
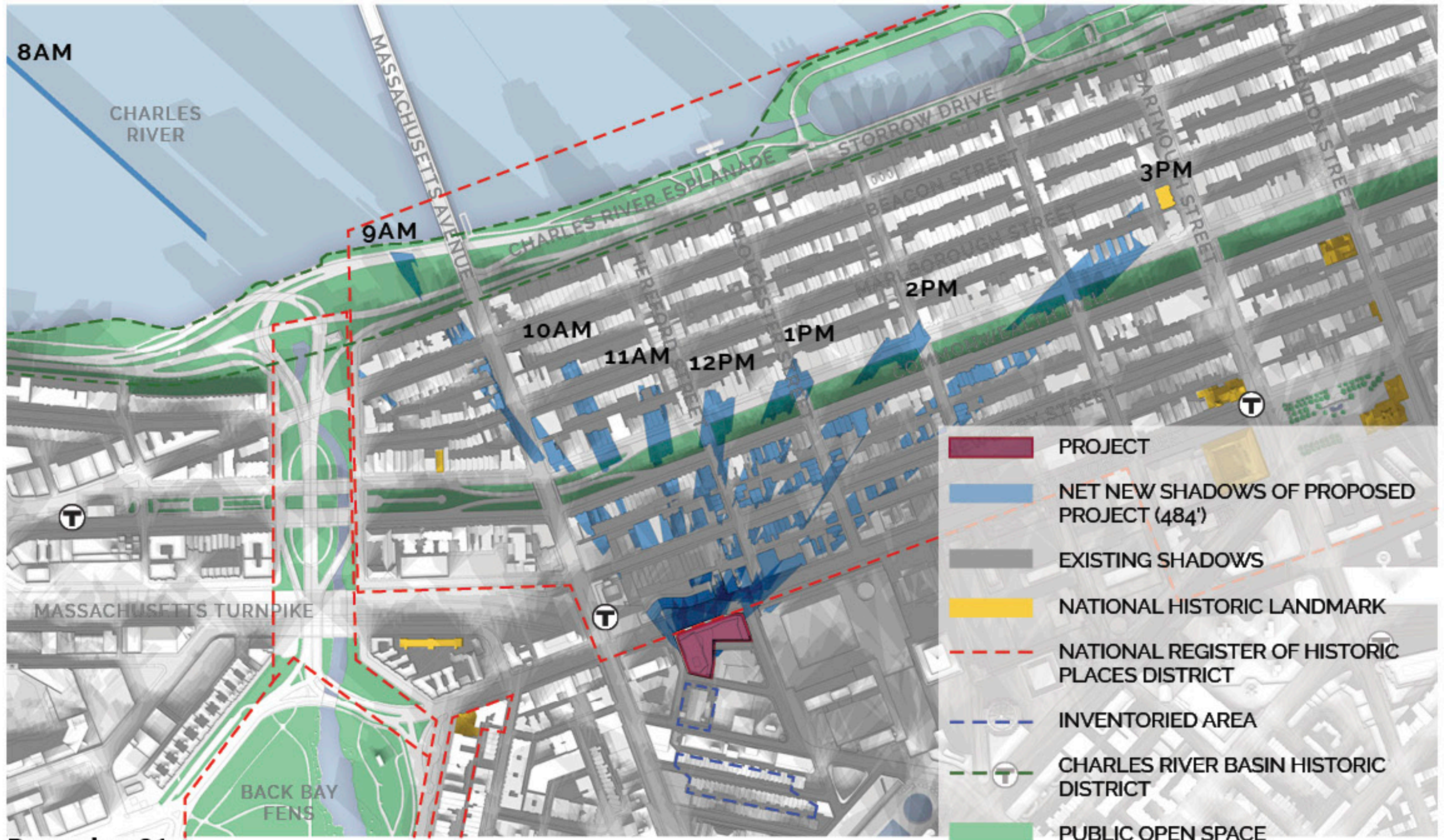
September 21st



October 21st



November 21st



December 21st

1000 BOYLSTON STREET
BOSTON, MASSACHUSETTS

SHADOW OVERLAP - SEPTEMBER 21 -DECEMBER 21

0 400' 800' N

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September 22, 2017

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Re: Full Scale Testing Paper Review

Dear Kevin,

As per your request, this letter is a follow-up to our discussion regarding the most accurate methodology to evaluate post-construction wind conditions. In particular, we have been asked to opine on the comparative accuracy of post-construction on-site full-scale wind measurements vs. wind tunnel testing for evaluating pedestrian wind conditions.

Since the 1960's, there have been significant advancements in modeling and measuring techniques used in boundary-layer wind tunnels for building design and city planning. Wind-tunnel testing has been widely used and regarded as the most accurate and reliable tool by all national and state building codes and by various municipal authorities, including the BPDA (ASCE/SEI, 2010, BRA 2006).

Compared to wind tunnel testing, full-scale measurements are expensive and time-consuming, but more importantly, they are impossible to perform in a meaningful manner for new buildings. They are rarely performed for commercial projects, but the limited full-scale data that is available can be used for validation of wind tunnel predictions. Therefore, literature on full-scale measurements for pedestrian winds and their comparisons with wind-tunnel results is also reviewed in this letter to support the use of wind tunnel testing.

Advantage of Wind-Tunnel Testing

As mentioned above, full-scale wind measurements are not only expensive and time consuming, but to be accurate, would require a sampling period measured in years. Most full-scale measurements are conducted at a few locations for a few days or a few weeks, when limited wind speeds and directions can be recorded. More importantly, without years of data, it is impossible to use the full-scale approach to obtain the future wind conditions around a new development before it is constructed.

Wind speeds at approximately 5 ft above grade (chest height) are most relevant to pedestrian comfort and safety. It is impractical to leave expensive measuring and recording devices at that height on public sidewalks, building entrances or outdoor seating areas for a long enough period of the time to obtain meaningful results of seasonal or annual wind conditions.

In contrast, wind-tunnel measurements are performed within a controlled environment where the atmospheric boundary-layer winds are simulated for 36 wind directions, taking into consideration the effect of surrounding buildings and upstream terrains. Depending upon the development size, it is common to have hundreds of wind speed sensors installed to fully cover the areas that may potentially be affected by the building(s) of interest. The directional wind speed ratios obtained from wind tunnel testing can be combined with long-term wind records from a reference site (e.g., Logan Airport) to predict wind speeds and exceeding frequencies on an annual or seasonal basis. In addition, if undesirable wind conditions are detected by wind-tunnel testing, mitigation measures can be quantitatively elevated in the tunnel for their effectiveness in wind control.

The entire wind-tunnel testing process can be completed within a relatively short time period and a limited budget to fulfill the requirements for assessing the wind environment around buildings.

A typical wind tunnel test is conducted for several building configurations. The difference in wind conditions between the existing (No Build), proposed (Build) and future (Full Build) configurations is often used to assess the potential wind impact of a new development. Because a direct comparison can be made between configurations tested this is one of the primary reasons that wind tunnel testing is widely used all over the world for assessing the pedestrian wind conditions around buildings.

Due to the obvious advantages of wind-tunnel testing over full-scale measurements, building codes and industrial standards typically recommend wind tunnel testing for studying wind effects around buildings. There are established testing procedures and requirements to ensure that reliable and repeatable wind tunnel results can be produced. Wind-tunnel testing is a well-established technology and, to our knowledge, no case-by-case validation of wind-tunnel predictions against full-scale data is required by building codes or municipal authorities.

Comparison with Full-Scale Measurements

Many full-scale measurements of wind speeds can be found in literature. One of the first comparisons of full-scale and wind-tunnel data was conducted in Canada in 1972. Full-scale wind speeds and directions were measured at seven locations in Commerce Court Plaza in downtown Toronto (Isyumov and Davenport, 1975). Despite several practical difficulties in collecting sufficient full-scale wind data, the agreement between wind-tunnel and full-scale mean wind speeds was found to be within about 10% for relatively windy areas of the plaza.

Kawamura et al (1988) carried out their full-scale measurements for a tall building in Hawaii in 1985. They measured not only the mean wind speed and direction, but also turbulence intensity, gust factor, and integral length of turbulence. Their later wind tunnel tests produced wind speed ratios that were generally higher than the field data, but the correlation coefficient between these two sets of data was found to be 0.79.

More recently, Visser and Cleijne (1994) conducted wind measurements for a low-rise complex and a high-rise building in the Netherlands. With the correct modelling of surrounding roughness, the wind tunnel tests produced a good prediction of the ratios between the local wind velocities at pedestrian height and the wind velocities at a reference height. In particular, for the wooded areas around the low building complex, the correlation between the full-scale and wind-tunnel measurements was between 0.92 and 0.99 for the winter and between 0.84 and 0.97 for the summer (when winds were generally calmer).

Full-scale measurements were also conducted by other researchers in Sheffield, UK (Lee and Hussain, 1979), Tokyo, Japan (Sanada et al, 1980), Brisbane, Australia (Letchford and Isaacs, 1992), Ottawa, Canada (Williams and Wardlaw, 1992) and New Zealand (Flay et al, 2013). These full-scale measurements have provided valuable data to validate the wind tunnel testing, which, in our opinion, remains as the most accurate and reliable tool for pedestrian wind studies.

Concluding Remarks

Wind-tunnel testing is considered as the most accurate and reliable technology for predicting wind conditions around buildings, whether for pre-construction modeling or for modeling post-construction conditions. Since the 1960’s, the technology has been advanced and validated by many researchers using full-scale measurements. On the other hand, full scale measurements take time and the alignment of several conditions to be meaningful.

Please let us know if you have any questions.

Yours truly,

RWDI

Hanqing Wu, Ph.D., P.Eng.
Technical Director/ Principal

Derek Kelly

Derek Kelly, M.Eng., P.Eng.
Project Manager / Principal

HW/DRK/aac
Attach.

References

ASCE/SEI (2010) “Minimum design loads for buildings and other structures”, ASCE/SEI 7-10, Reston, VA.

BRA (2006) “Development Review Guidelines”, One City Hall Square, Boston, MA 02201.

Flay, R.G.J., Carpenter, P., Revell, M., Cenek, P., Turner, R. and King, A. (2013) “Full-scale wind engineering measurements in New Zealand”, Proceedings of the Eighth Asia-Pacific Conference on Wind Engineering, Chennai, India.

Isyumov, N. and Davenport A.G. (1975) “Comparison of full-scale and wind tunnel wind speed measurements in the Commerce Court Plaza”, Journal of Industrial Aerodynamics, 1, 201-212.

Kawamura, S., Kimoto, E., Fukushima, T. and Taniike, Y. (1988) “Environmental wind characteristics around the base of a tall building – a comparison between model test and full scale experiment”, Journal of Wind Engineering and Industrial Aerodynamics, 28, 149-158.

Lee, B.E. and Hussain, M. (1979) “The ground level wind environment around the Sheffield University Arts Tower”, Journal of Wind Engineering and Industrial Aerodynamics, 4, 333-341.

Letchford, C.W. and Isaacs. L.T. (1992) “Full scale measurement of wind speeds in an inner city”, Journal of Wind Engineering and Industrial Aerodynamics, 41-44, 2331-2341.

Sanada, S, Iwasa, Y. and Yoshida, M. (1988) “Full scale measurement of environmental wind in the Shinjuku New Metropolitan Center”, Journal of Wind Engineering and Industrial Aerodynamics, 28, 129-138.

Visser, G. Th. And Cleijne, J.W. (1994) “Wind comfort predictions by wind tunnel tests: comparison with full-scale data”, Journal of Wind Engineering and Industrial Aerodynamics, 52, 385-402.

Williams, C.D. and Wardlaw, R.L. (1992) “Determination of the pedestrian wind environment in the City of Ottawa using wind tunnel and field measurements”, Journal of Wind Engineering and Industrial Aerodynamics, 41-44, 255-266.

APPENDIX A

$\overline{V}$. mean plaza wind speed 9' above ground
$\overline{V}_{937}$ mean top of building speed
$\overline{V}_{g}$ mean gradient wind speed.

Journal of Industrial Aerodynamics, 1 (1975) 201—212

COMPARISON OF FULL-SCALE AND WIND TUNNEL WIND SPEED MEASUREMENTS IN THE COMMERCE COURT PLAZA*

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(Received March 4, 1975)

Summary

This paper presents comparisons of full-scale measurements of the mean wind speed and mean wind direction at several points in a plaza located in a built-up urban environment with similar measurements obtained in a scaled boundary layer wind tunnel model study. Full-scale measurements were carried out with a portable propeller vane anemometer positioned at a height of 9 ft. above local ground. Full-scale measurements were carried out over approximately a two-week period. Wind tunnel measurements of wind speed were carried out with special single-ended hot film anemometer probes. Measurements of wind direction in the wind tunnel were made with a flow indicator consisting of a light sphere mounted on a flexible support.

Although the full-scale data base was not adequate to allow a comprehensive comparison, the agreement between the full-scale and model observations was encouraging, particularly in windy areas of the plaza. The agreement between wind tunnel and full-scale mean wind speeds was found to be within about 10% for relatively windy areas of the plaza.

Introduction

A study of wind effects for the Commerce Court project, Toronto, (see Fig. 1) was carried out at the Boundary Layer Wind Tunnel Laboratory to provide various design information. The study comprised the definition of the gradient wind speed statistics for the Toronto area and a wind tunnel investigation of the aeroelastic response, exterior pressures and the pedestrian level wind environment. The wind tunnel model study was carried out in the approximately 100-ft.-long boundary layer wind tunnel of the Laboratory at a geometric scale of 1:400. Representative flow regimes were developed by generating deep turbulent boundary layer flows over long model fetches of suitably roughened upstream terrain. Details of the experimental procedure and the results of the study pertaining to the wind induced pressures, forces and structural response and to the pedestrian level wind environment are given in refs. [1] and [2], respectively.

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* Paper presented at The Symposium on Full-Scale Measurements of Wind Effects on Tall Buildings and Other Structures, University of Western Ontario, 23—29 June 1974.

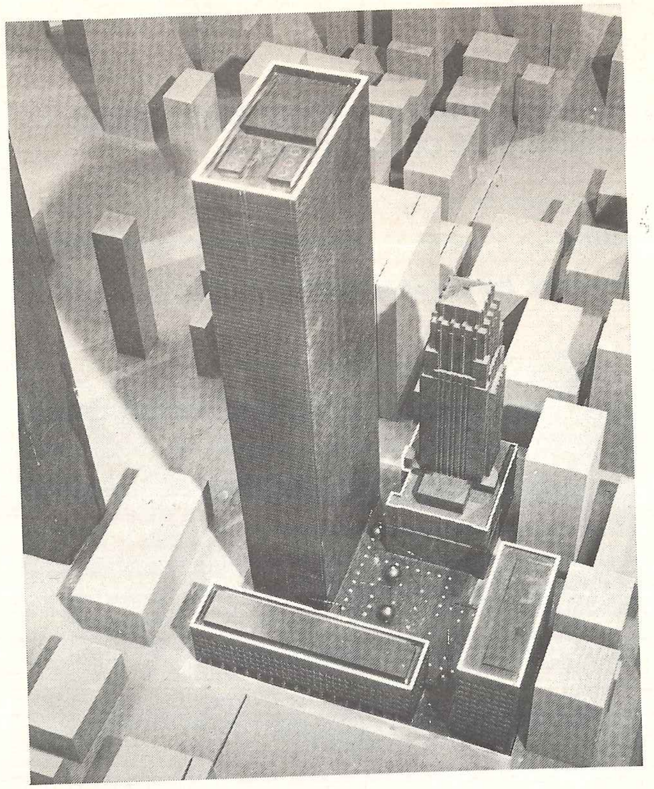


Fig. 1. View of 1:400 scale model of Commerce Court project.

The wind tunnel investigation of the pedestrian wind climate comprised smoke visualization of the overall flow field and quantitative measurements of wind speed and wind direction at some 20 locations (12.5 ft. above local ground) for a full range of azimuth direction. Predictions of the pedestrian level wind speeds, provided from an integration of the quantitative wind tunnel speed data with the probability distribution of gradient wind speed for the Toronto area, indicated that certain areas of the plaza are likely to experience rather high wind speeds. Typically mean wind speeds (hourly mean) of about 17 mph were predicted to be exceeded 10% of the time at some locations during the winter (January to March) [2]. Possible modifications were deferred until actual conditions were experienced.

Full-scale experience during the first winter of operation proved to be consistent with wind tunnel predictions. The plaza environment was indeed found to be quite windy, especially during the winter months. Furthermore, the locations of areas, where particularly windy conditions were encountered in full scale, were generally in accord with wind tunnel findings. In the fall of 1972, a programme of remedial measures for the upcoming winter was considered. Prior to the implementation of any wind tunnel derived corrective

measures, some specific comparisons of the full-scale wind speed environment with wind tunnel results were considered desirable.

Full-scale measurements of wind speed and direction were made at 7 locations in the Commerce Court Plaza during December 1972. Due to practical considerations, these measurements were carried out at a height of 9 ft. above local ground rather than the height of 12.5 ft. used in the earlier model study. The results of these measurements were in reasonable agreement with the findings of the initial Commerce Court wind tunnel study [2]. Nevertheless, to provide more direct comparisons with these full-scale data, further wind tunnel measurements were made using an updated model of the surroundings, which had changed somewhat since 1968. These measurements were carried out using hot-film anemometer sensors located at a height corresponding to 9 ft. full-scale. The wind tunnel wind speed comparisons presented here are based on the findings of this more recent study.

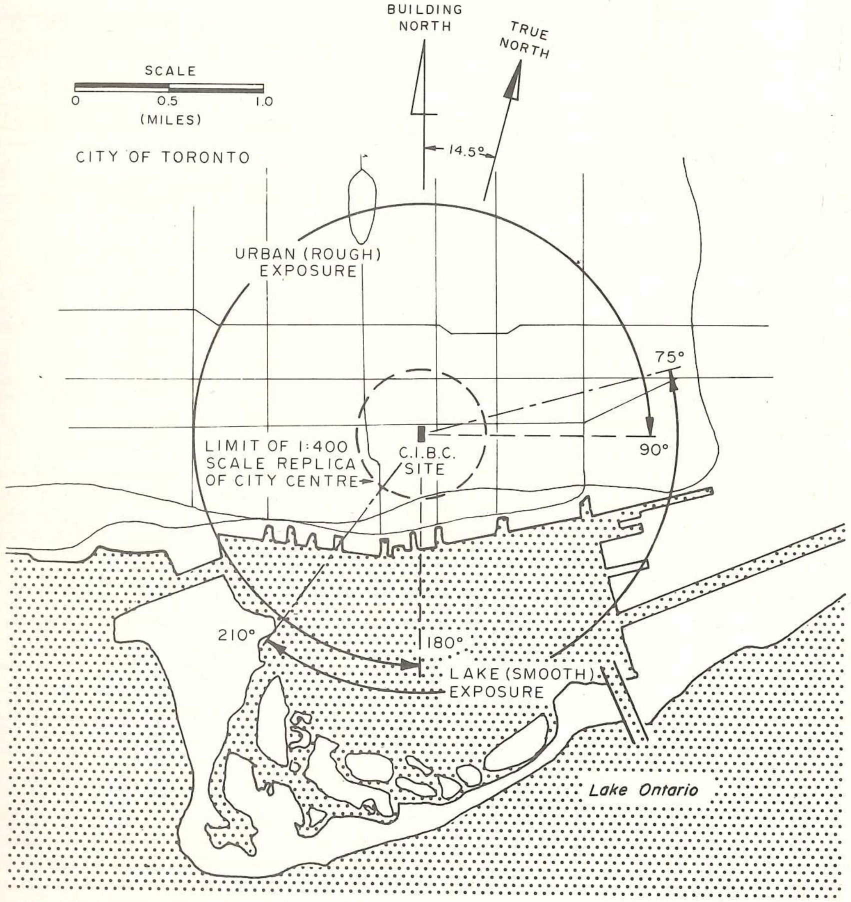


Fig. 2. Commerce Court site map.

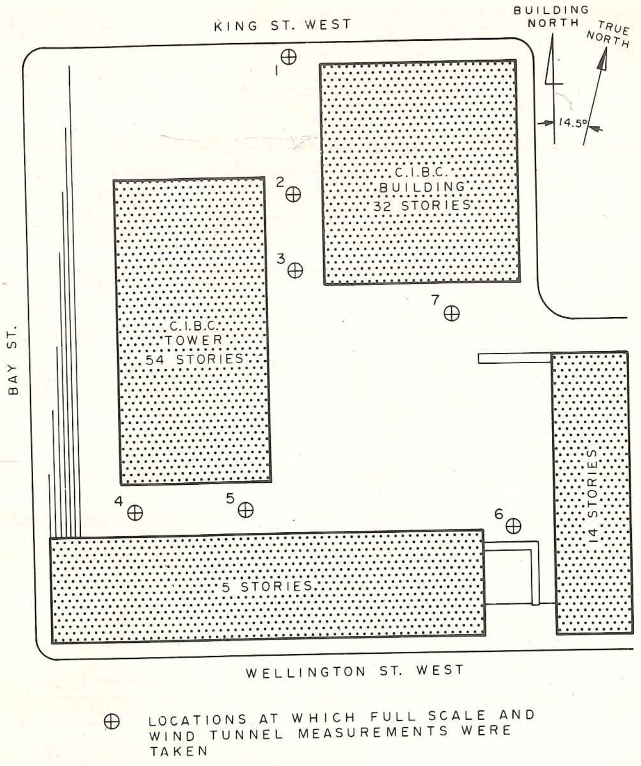


Fig. 3. Plan of wind speed and wind direction measuring locations.

Wind tunnel measurements

A view of the wind tunnel model of the Commerce Court Plaza bounded by the 786-ft. Canadian Imperial Bank of Commerce (CIBC) Tower, the original CIBC building and two office buildings is presented in Fig. 1. The model was constructed at a geometric scale of 1:400. All major buildings within a full-scale radius of 1600 ft. from the plaza were reproduced in block outline form in order to simulate the effect of the immediate environment on flow conditions in the plaza. The properties of the flow approaching this "proximity" model were matched to properties of the full-scale wind over fetches representative of the surrounding terrain. As seen from the map depicted in Fig. 2, the site is surrounded by rough urban terrain from the north (approximately from SW to E) and by open water from the south (approximately from E to SW). The extent of the two wind tunnel exposures selected to be representative of the full-scale urban (rough) and lake (smooth) exposures, indicating their overlap, is shown in Fig. 2. Details of the model flow properties for these exposures are given elsewhere [1].

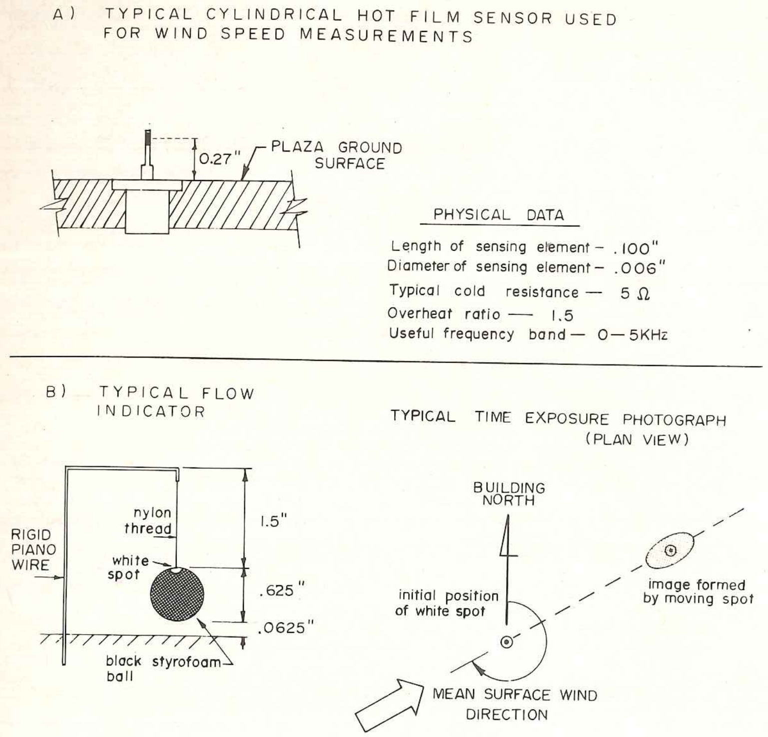


Fig. 4. Wind speed and direction measuring devices used in wind tunnel study.

The plaza locations for which wind tunnel model and full-scale wind measurements are presented are shown in Fig. 3. Wind tunnel measurements of wind speed were made at all 7 locations for a full range of gradient wind direction in increments of 15 degrees. The gradient wind direction a_g was measured clockwise with $a_g = 0°$ corresponding to the building north (14.5° W of true north). Model plaza wind speed measurements were made with cylindrical single-ended hot-film anemometer probes protruding vertically above the plaza. The sensors were insensitive to the local wind direction and only provided information on the local wind speed. Details of these sensors are summarized in Fig. 4. In all cases, the anemometer bridge output was linearized. The linearized anemometer output was sampled and analysed with an on-line digital computer data acquisition system to provide information on the peak, mean and r.m.s. (root-mean-square) wind speed as a ratio of the gradient mean wind speed at each location for all values of a_g examined. Only mean wind speed data are presented here.

Measurements of local wind direction a were made with flow indicators schematically described in Fig. 4. Each indicator consisted of a 3/8-in.-diameter hollow polystyrene sphere suspended by a nylon thread from a gallows of piano wire. The sphere was painted black with a white spot near the apex. Time exposure photographs of the horizontal movement of the dot provided an indication of both the local wind speed and direction. The mean surface wind direction was obtained for each value of a_g from the image of the envelope of motion of the white spot on the flow indicator, with respect to the image of the spot in still air. In the initial wind tunnel measurements for the Commerce Court Project [2], this technique was used to provide information on both the mean and fluctuating flow components. This method of measuring surface wind speed was subsequently replaced by the use of the single-ended hot-film anemometers as described above.

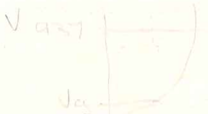
Full-scale measurements

Full-scale measurements of both wind direction and wind speed were carried out at all 7 plaza locations shown in Fig. 3. Measurements were made at a height of 9 ft. above local ground with a propellor-vane anemometer mounted on a portable tripod. At each plaza location readings of wind speed, taken at intervals of about 6 s, were manually recorded over a period of 5 min. The range of wind direction and an estimate of the average wind direction during this interval were also recorded. Measurements were made sequentially at all seven plaza locations twice a day during a two week period. During these periods, continuous measurements of wind speed and wind direction were made by members of the Division of Building Research of the National Research Council, using instrumentation positioned on a mast above the CIBC Tower at approximately 937 ft. above plaza level [4].

Wind speeds were found to vary significantly over the two week period of observations. Maximum five minute average wind speeds at the anemometer above the CIBC tower during this period were about 50 mph (22 m/s). The mode of the extreme annual hourly gradient wind speeds for the Toronto area is about 73 mph (33 m/s). Very low wind speeds (less than 5 mph or 2.2 m/s) at 937 ft. above plaza level were experienced on some occasions.

The analysis of the full-scale data proceeded as follows. Five-minute average wind speeds were computed for each of the observation periods at all plaza locations. These were divided by the average wind speed at the 937-ft. level for the corresponding five-minute period to obtain speed ratios or speed coefficients. The average wind direction at the 937-ft. level, obtained for the same five-minute period, was taken as the mean gradient wind direction a_g associated with each of the speed ratios. The average plaza wind speeds were subsequently expressed as ratios of the gradient wind speed. Typically, for plaza location "*i*", the average wind speed for a gradient direction a_g, expressed as a ratio of the gradient speed, becomes:

$$\frac{\overline{V}}{\overline{V}_g}(a_g) = A(a)\,\frac{\overline{V}}{\overline{V}_{937}}(a_g)$$



$\frac{V_{937}}{V_g} = .88$

$V_g = \frac{V_{937}}{A(a)}$

Here $\overline{V}$, $\overline{V}_{937}$ and $\overline{V}_g$ are the mean plaza wind speed (at 9 ft. above ground), the mean speed as measured with the mast anemometer and the mean gradient wind speed for a gradient wind direction a_g. The conversion factor to gradient height $A(a_g) = \overline{V}_{937}(a_g)/\overline{V}_g(a_g)$, from small-scale topographic wind tunnel model measurements [1] was found to vary between 0.86 to 0.90 depending on a_g. In view of the uncertainties associated with wind tunnel modelling of natural wind, this variation was not regarded to be significant and $A(a_g)$ was taken as 0.88 for all gradient wind directions.

Comparison of full-scale and model results

Comparisons of wind tunnel derived and full-scale mean wind speed coefficients (expressed in terms of the gradient wind speed), for the seven plaza locations studied, are presented in Fig. 5. Although in some cases there are noticeable differences between full-scale and model data the overall agreement is reasonable. Since wind tunnel results are essentially representative of conditions during periods of neutral atmospheric stability, it was initially anticipated that best agreement would result for full-scale data obtained at high wind speeds. This proved not to be the case with the exception of data for a few near-calm periods which are excluded from the presented comparison. As seen from the mean gradient wind speeds ($\overline{V}_g = \overline{V}_{937}/0.88$), indicated beside each of the full-scale data points, no trend towards improved agreement between full-scale and model results with increased $\overline{V}_g$ is apparent. Differences between model and full-scale data appear to be more or less random, with the exception of wind from the north-west quadrant where full-scale data are generally somewhat higher. This suggests that there are no major disparities between the overall model and full-scale flow regimes and that existing differences are largely attributable to the following:

(i) differences in local model and full-scale flows at particular locations resulting from slight dissimilarities between model and full-scale geometry of the solid boundaries and dissimilarities of plaza occupancy;

(ii) experimental errors resulting from the relative spatial misalignment of model and full-scale measuring instruments;

(iii) direct measuring errors; and

(iv) errors in estimates of the mean wind speed ratios resulting from the statistical variability inherent to both model and full-scale flow fields.

Errors associated with (i) and (ii) above are particularly difficult to assess without extensive sensitivity studies of the various wind speed measurements to slight changes in geometry; changes in instrument location; and changes of the micro features of the plaza; namely, occupancy by people and various objects. For example a 50-ft.-high Christmas tree was located in the middle of the plaza during the full-scale measurements. Errors associated with (iii) and (iv) although also difficult to quantify can be assigned reasonable expected bounds. From repeatability measurements, the normalized standard model errors, including both measuring errors and statistical variability are

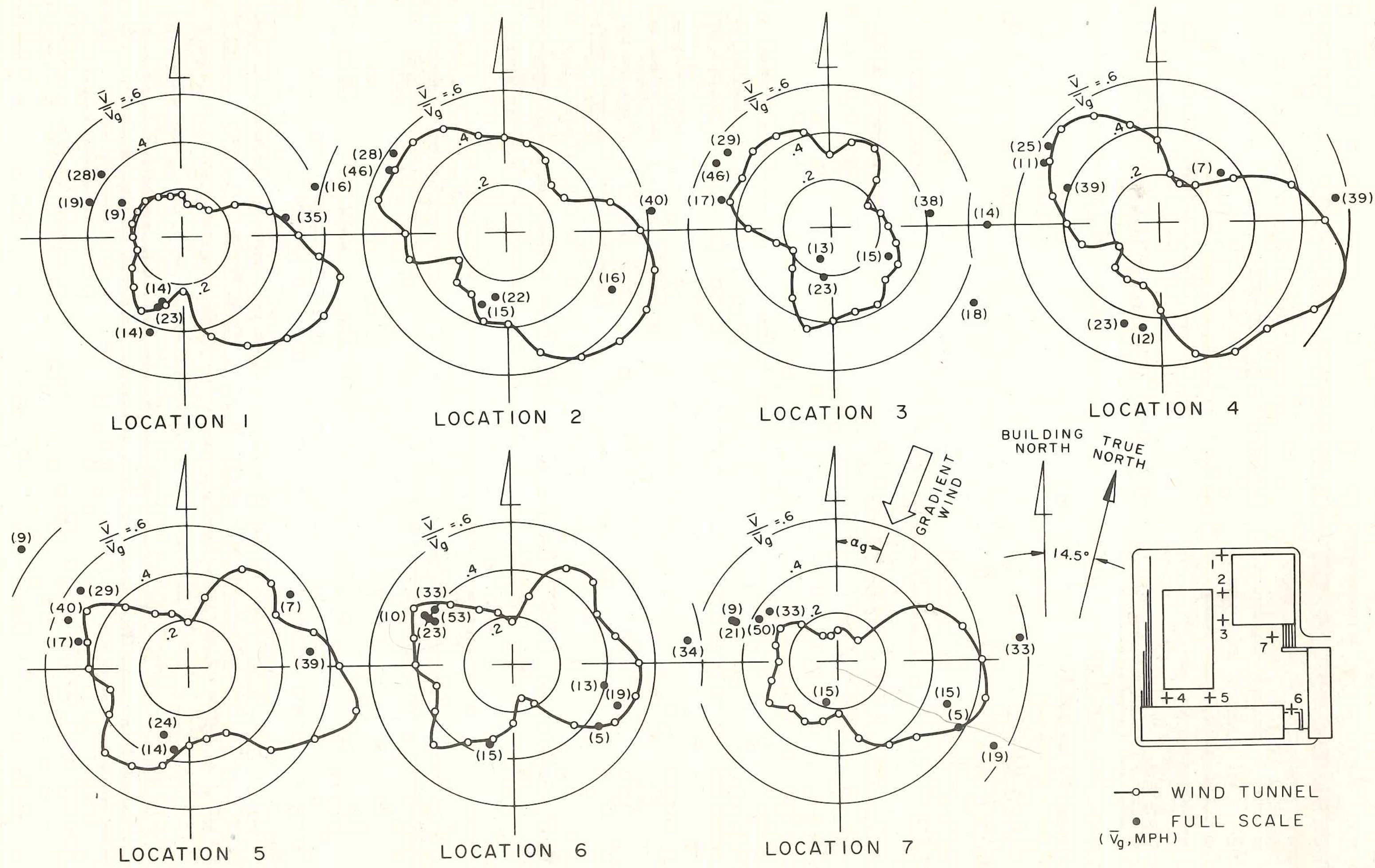


Fig. 5. Comparison of full-scale and wind tunnel measurements of mean wind speed at locations studied.

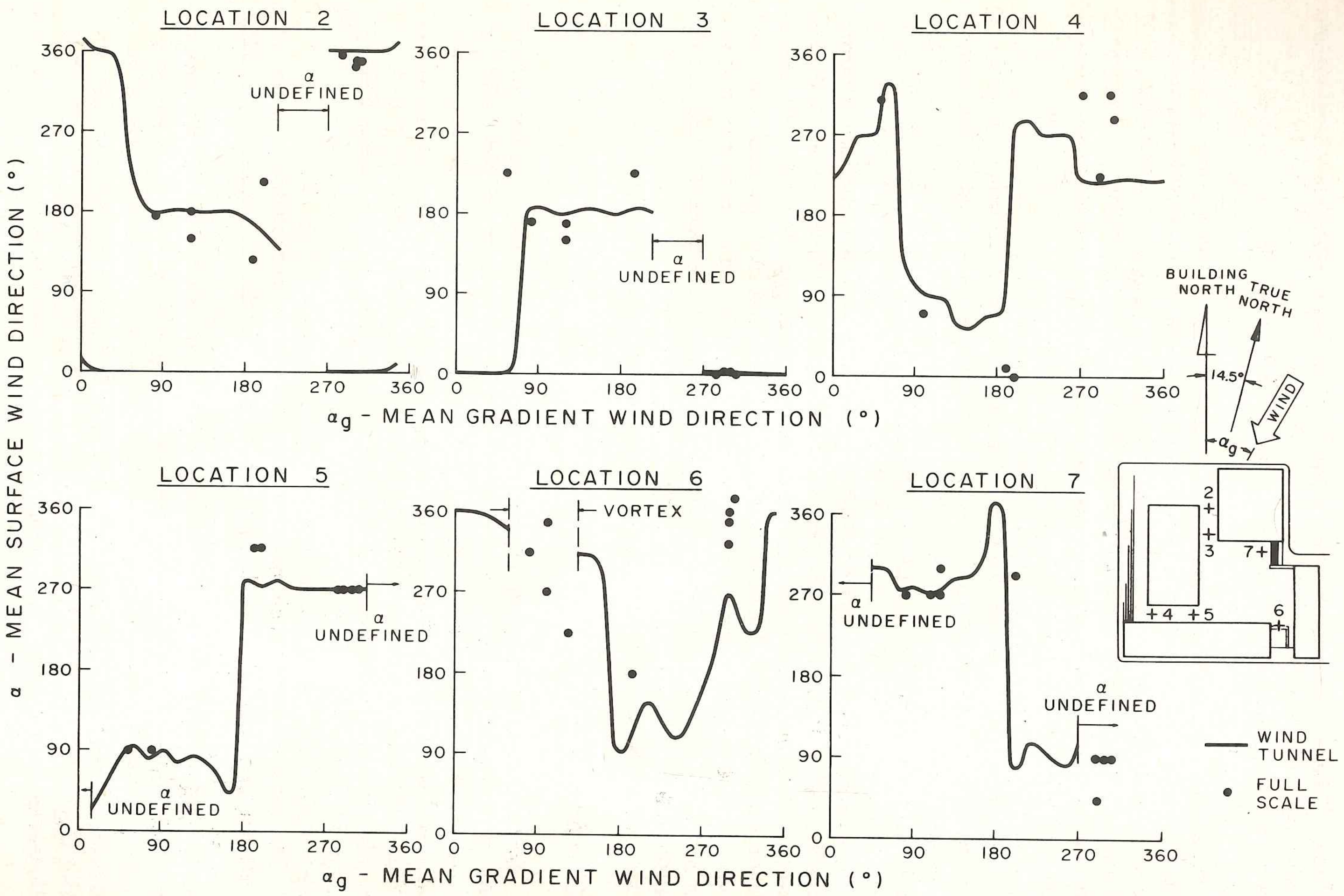


Fig. 6. Comparison of full-scale and wind tunnel measurements of surface wind direction at locations studied.

about 5% for the hourly mean wind speed ratios. Normalized standard errors, considered representative of the full-scale measurements including both experimental inaccuracies and increased statistical variability, as speed ratios are based on 5 min rather than 1 h averages, are at least 10—20%. This greater variability in the full-scale measurements can be seen from the rather large differences in full-scale wind speed ratios obtained for similar wind directions. The additional variability due to 5 min as opposed to 1 h averaging comes from the energy under the microscale spectrum of turbulence in the frequency band of 1—12 cycles per hour. Taking the above indicated uncertainties into account the agreement between wind tunnel and full-scale data presented in Fig. 5 is indeed quite encouraging.

Comparisons of the prevailing wind direction at plaza locations 2—7 obtained in the wind tunnel and in full scale are presented in Fig. 6. The comparison is mainly a qualitative one. Plaza wind directions in both model and full scale were found to be associated with marked fluctuations (typical range of about 50°). Full-scale estimates of the prevailing wind direction are consequently associated with significant errors. The wind direction at locations 3 and 5, located in passageways, was essentially parallel to the passageways and, depending on the gradient wind direction, either into or out of the plaza. The variation of the surface wind direction at location 2, 4 and 6 with a_g was more complex. It was interesting to note that the wind direction at location 7 was largely determined by reverse flow resulting either from the horizontal standing vortex in front of the main CIBC Tower for easterly directions or the wake behind the main tower for westerly winds.

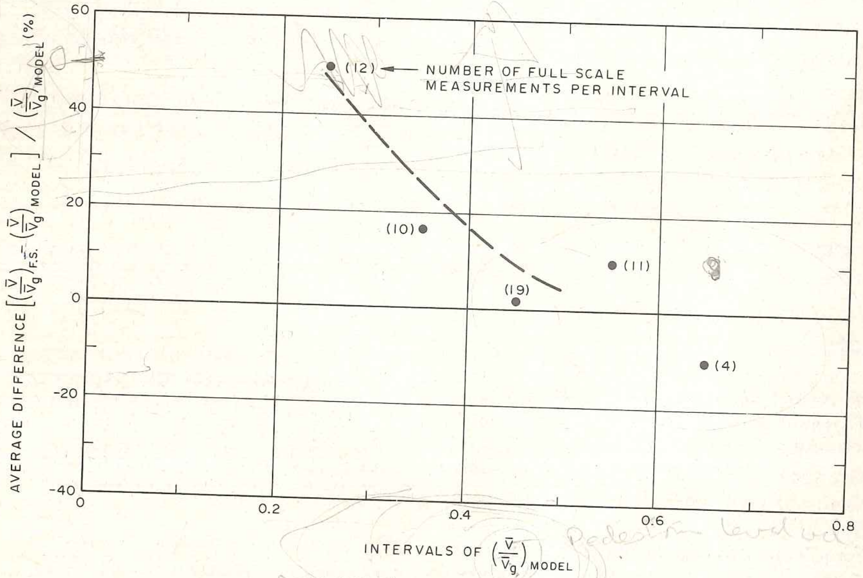
Concluding remarks

Comparisons of wind tunnel measurements with full-scale counterparts are generally associated with practical difficulties. In addition to differences resulting from incomplete similarity between model and full-scale processes, such comparisons are often complicated by the variability inherent to atmospheric phenomena, which generally precludes controlled full-scale experiments. Further to the problem of obtaining sufficient representative full-scale data, it is often very difficult to obtain such data in a form which would permit direct comparisons with wind tunnel model findings.

The number of full-scale measurements of wind speed, available to the authors, in the Commerce Court Plaza, was insufficient to permit a full evaluation of the wind tunnel findings. Indeed, only spot comparisons were possible for a limited number of gradient wind directions. On the other hand, the availability of simultaneous wind speed and wind direction records at a height of 937 ft. above the plaza permitted the reduction of the full-scale data to a form which was directly comparable with wind tunnel results. In this regard, the presented full-scale comparisons, despite their inherent statistical scatter, are of practical importance.

As mentioned above, the agreement of the available full-scale wind speed data with wind tunnel findings is generally good if cognizance is made of the variability inherent to both model and full-scale data. A statistical analysis, carried out on the differences existing between $(\overline{V}/\overline{V}_g)$ model and $(\overline{V}/\overline{V}_g)_{\text{f.s.}}$ at coincident values of a_g for each of the seven plaza locations, indicated no significant differences between model and full-scale data. From the Student's *t*-test carried out for comparable model and full-scale data at each location, the expected percentages of time during which existing differences would be exceeded are 6, 80, 70, 6, 48, 56 and 10 for locations 1—7, respectively. This suggests that with the scatter present in the full-scale data, there are no statistically significant differences between the model and full-scale speed ratios at each of the plaza locations. An assessment of the overall agreement is obtained from an examination of the average percentage differences between model and full-scale ratios of $\overline{V}/\overline{V}_g(a_g)$ for all plaza locations. Rather than to obtain the average percentage difference for all measurements combined, it is, from a practical aspect, more useful to look at the average percentage differences for different magnitude intervals of $\overline{V}/\overline{V}_g$. Average differences between full-scale and wind tunnel derived mean plaza wind speed ratios are depicted in Fig. 7. Here the differences expressed as percentages of $(\overline{V}/\overline{V}_g)_{\text{model}}$ are given for a number of intervals of $(\overline{V}/\overline{V}_g)_{\text{model}}$. Although the percentage differences are rather high, when low wind speeds relative to $\overline{V}_g$ are experienced at plaza level, the agreement is much improved for rela-

ERROR



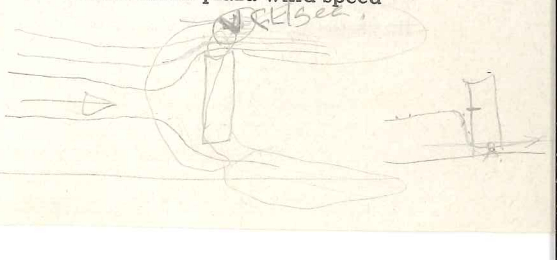
70×10³
20×10³
4×10
2×10

Pedestrian level vel

AMOUNT OF VEL INCREASE

Fig. 7. Average differences between full-scale and wind tunnel mean plaza wind speed ratios.

10ft
20ft
V_g
Free Stream Vel.



tively windy plaza areas. The agreement within about 10%, on the average, between windy plaza conditions in model and full scale is indeed encouraging as it implies that representative wind tunnel model methods can effectively provide information on the more important aspects of the surface wind speed climate. Further comparisons, of course, are required to lend support to the findings presented. Also it is desirable to obtain comparisons of the fluctuating or turbulent wind regime.

It should be stressed in closing, that a representative simulation of the overall full-scale flow regime is a prerequisite to effective wind tunnel assessments of the flow around and within building complexes. Experience at the Boundary Layer Wind Tunnel Laboratory indicates that pedestrian level flow conditions even in a very built-up environment are quite sensitive to the structure of the approaching wind. Consequently, in boundary layer wind tunnel simulations it is important to representatively model both the immediate proximity of the area of interest as well as the structure of the approaching flow.

Acknowledgements

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References

1 A.G. Davenport, M. Hogan and N. Isyumov, A study of wind effects on the Commerce Court Tower, Part I, Univ. of Western Ontario, Engineering Science Research Rept. BLWT—7—69.
2 A.G. Davenport, C.F.P. Bowen and N. Isyumov, A study of wind effects on the Commerce Court project, Part II, Univ. of Western Ontario, Engineering Science Research Rept. BLWT—3—70.
3 R.F. Grigg, The study of pedestrian level wind conditions at the Commerce Court, Toronto, Engineering Science B.E.Sc., Thesis, Univ. of Western Ontario, March, 1974.
4 A. Dalgliesh, Wind pressure measurements on the Commerce Court Building, Toronto, Symp. on Full-Scale Measurements of Wind Effects on Tall Buildings and Other Structures, Univ. of Western Ontario, June 1974.

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Short Communication

FULL-SCALE COMPARISON OF A WIND-TUNNEL SIMULATION OF WINDY LOCATIONS IN AN URBAN AREA*

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Summary

Thermal and mechanical comfort of pedestrians is an important design criterion used in planning urban spaces and in locating urban trees and protective windbreaks [1,2]. Wind-tunnel flow-visualization techniques have been used to determine relatively windy regions of urban areas (e.g. see refs. 3-6). Of the different forms of flow visualization, erosion techniques have the advantage of being sensitive to gusts of wind, commonly the cause of pedestrian discomfort [4], and results can be partially quantitative.

Few wind-tunnel simulations have been validated by full-scale comparisons and it is often recommended that more full-scale measurements be made (e.g. in ref. 6). In one comparison of model measurements obtained using a hot-wire anemometer with full-scale measurements of ground-level winds in an urban area, there was considerable scatter in the ratio of ground-level to gradient windspeed, particularly close to buildings [6]. From the data reported for a similar study by Chock [7], a correlation coefficient (r) of 0.82 can be calculated between comparable full-scale and model measurements; but Chock concluded that the full-scale measurements were too few in number for complete validation. Durgin and Chan [5] found close correlation between wind-tunnel simulations with hot-wire and erosion techniques, but full-scale measurements were not included.

This study compares full-scale wind measurements made with hand-held anemometers with results of a previous study in which relative ground-level windspeeds across a diverse urban area were simulated by an erosion technique. The initial objective was to determine whether the model was able to distinguish zones of significantly higher mean windspeed. Additionally, the effect of atmospheric thermal stability on windspeeds in the Central Business District (CBD) was evaluated.

The previous study was a wind-tunnel simulation of the Dayton CBD conducted in the Wright Brothers Memorial wind tunnel facility at the Massachusetts Institute of Technology. The simulation methods of that particular study are outlined in ref. 8; more details of the erosion technique and tunnel facility are given in refs. 5 and 6. Briefly, plastic pellets were spread across the floor of a 600:1 model of the CBD, and pellet scouring patterns were photographed as the gradient wind-

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speed [8] was increased in steps of about 5 or 10 mph (2.2 or 4.5 m s^{-1}). No scouring occurred at 20 mph. Scouring at 30 mph occurred in the vicinity of tall buildings. Roughly half the pelleted area was still unscoured at 50 mph.

1. Methods

For the present study, ten sites in the Dayton CBD were chosen for full-scale measurement for each of two wind direction classes, southwest (SW) and northwest (NW). In the wind-tunnel study, eight of these sites (4 SW, 4 NW) showed scouring at a tunnel gradient wind speed of 30 mph (13.4 m s^{-1}), one additional site (NW) showed scouring at a tunnel gradient wind speed of 40 mph (18.0 m s^{-1}), another additional site was scoured at 50 mph (22.4 m s^{-1}), and ten sites (5 SW, 5 NW) did not show scouring even at 50 mph. Some sites were included in both SW and NW full-scale measurements, so that there was a total of only 15 different measurement sites (Fig. 1).

Full-scale data collected in the CBD consisted of windspeed measurements and direction estimates at 30-s intervals for 0.5-h periods. Speeds were mea-

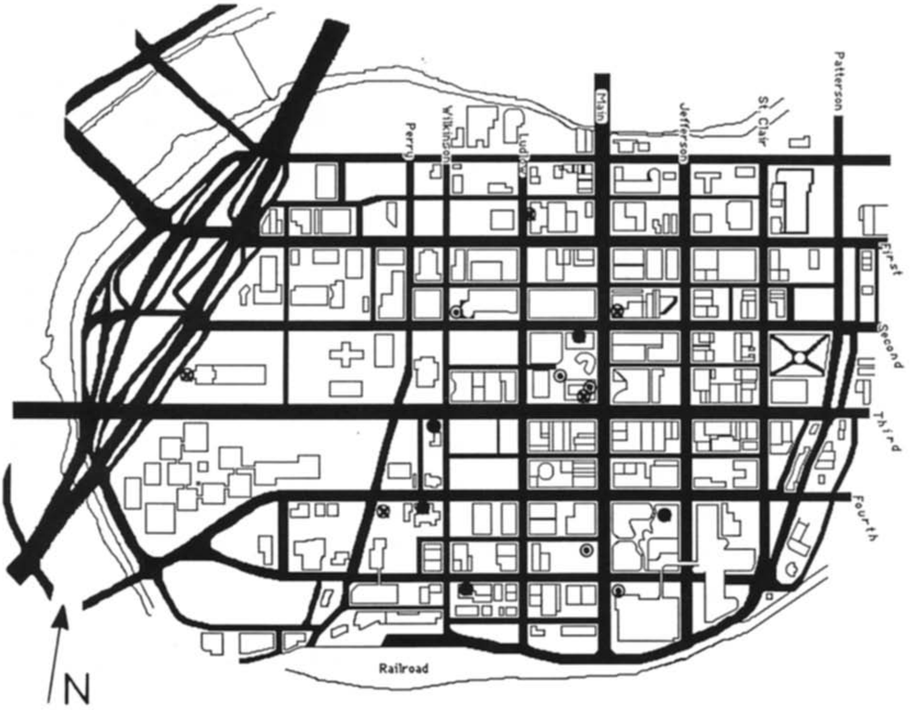

Fig. 1. Dayton, OH, measurement sites. Measurement sites used when the wind was predominantly from the NW (⊗), SW (⊙), and in both measurement networks (●).

sured at 1.4 m above ground with 10 Dwyer* wind meters. The measurements were replicated eight times for NW winds and ten times for SW winds.

The Dwyer meter operates by a pressure differential acting on a small polystyrene ball. It has a low scale from 1.5 to 10 mph (0.7 to 4.5 m s^{-1}) and a high scale from 4 to 30 mph (1.8 to 13.4 m s^{-1}). The meter has a directional response that we found to fall off approximately as cos $\theta^{1/3}$, where θ is the angle that the face of the anemometer deviates from perpendicular to the wind direction in the horizontal plane. Hence, for winds within 30° of the perpendicular, response is nearly full and directionality is probably not a significant cause of error. Wind-tunnel calibrations of the meters for both windspeed scales were made at the beginning and at the end of the series of 18 measurement periods. Changes in calibration were assumed to be linear with length of time in use and adjustments were made accordingly. The high-speed scale produced more variable readings and less satisfactory calibration equations than the low scale. Because of this, all high-scale readings (1.6% of all measurements) were excluded from the analysis.

Reference windspeed and direction were obtained from the weather station at the Dayton International Airport 15 km north of the city. Measurements were taken during periods in which the windspeeds were between 7 and 16 mph (3.3 and 7. 2 m s^{-1}). Examination of the airport windspeed record for a previous year showed that our measurements were made during wind conditions representative of about 19% of the year. During measurements, gradient winds (calculated from the published 00Z National Weather Service 500-mbar level map) over the city ranged from <5 m s^{-1} to 57 m^{-1}, but for 12 of the 18 periods they were greater than 18 m s^{-1}.

The airport windspeed, U_a, at 1.4 m was calculated from the windspeed measured at 11 ft (3.3 m) by assuming a logarithmic profile and using a calculated friction ve locity [9] (Table 1), a universal momentum function derived from Pasquill stability classes [10], and an assumed airport roughness length (z_0) of 0.02 m according to ref. 11. U_a averaged 5.0 m s^{-1} with NW winds and 6.4 m s^{-1} with SW winds.

The general method of analysis was by one-tailed t-test comparisons between the sites that were scoured (S_{40} sites) and those that were unscoured (U_{40} sites) at the 40 mph wind-tunnel gradient speed. Four wind variables were evaluated: mean windspeed (U_{mean}), mean dimensionless windspeed ($U_c = U_{mean}/U_a$), turbulence intensity (I), and an effective windspeed (U_{eff}). U_{eff} ($U_{eff} = U_{mean} + 3.5\times$ (r.m.s. windspeed) [12]) provided an index of pedestrian comfort.

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*Mention of a commercial or proprietary product does not constitute endorsement by the USDA or the Forest Service.

TABLE 1

Measurement times and airport wind conditions during the 18 measurement period

Wind direction	Date	Number of periods	Windspeed at 1.4 m ($m\ s^{-1}$)	Friction velocity ($m\ s^{-1}$)
NW	4/20/83	2	3.0	0.47
	5/26/83	2	3.4	0.47
	7/05/83	2	4.0	0.54
	7/12/83	2	2.4	0.38
SW	4/27/83	1	3.8	0.51
	5/04/83	2	4.3	0.58
	5/20/83	2	4.0	0.55
	5/31/83	2	4.3	0.58
	7/01/83	2	4.0	0.54
	9/26/83	1	2.2	0.35

2. Results

In the CBD, U_{mean} for the U_{40} sites averaged 85% and 76% of U_{mean} in the S_{40} sites for the NW and SW wind directions respectively (Table 2). U_c for S_{40}

TABLE 2

Means, standard deviations (SD), and results of t tests on sites scoured at 40 mph (S_{40}) and those unscoured at 40 mph (U_{40}) (significance of the comparisons is given by α values)

Variable	Site type	NW wind direction				SW wind direction			
		n	Mean	SD	α	n	Mean	SD	α
U_{mean} ($m\ s^{-1}$)	S_{40}	38	2.03	0.57	0.002	40	2.57	0.91	<0.001
	U_{40}	39	1.63	0.51		59	1.80	0.44	
U_c	S_{40}	38	0.64	0.20	0.006	40	0.67	0.23	<0.001
	U_{40}	39	0.52	0.18		59	0.47	0.11	
I	S_{40}	38	3.2	1.0	0.62	40	3.2	1.2	0.91
	U_{40}	39	3.4	1.5		59	3.2	0.9	
U_{eff} ($m\ s^{-1}$)	S_{40}	38	5.0	1.9	<0.001	40	6.3	2.2	<0.001
	U_{40}	39	3.6	1.5		59	4.1	1.9	

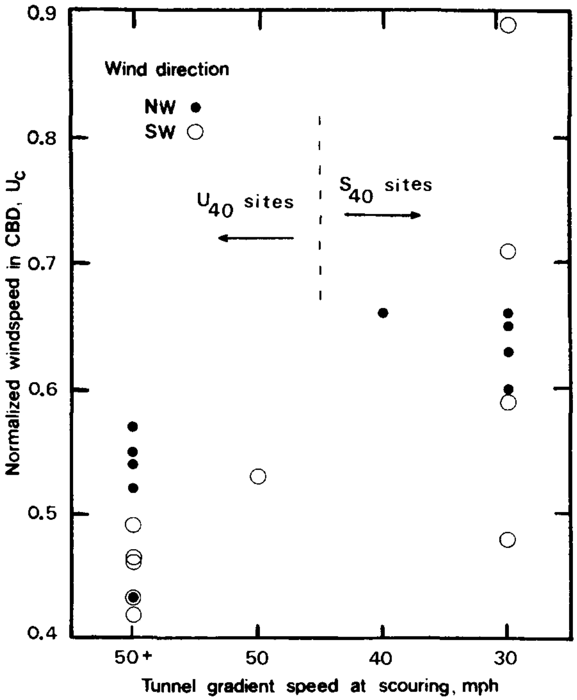

Fig. 2. Normalized windspeed, U_c, in the full-scale study versus gradient speed in the wind-tunnel study at which pellet scouring occurred (1 mph = 0.447 m s^{-1}). Each point represents the average of six to ten 0.5-h periods. All sites at 50+ mph were not scoured even at 50 mph. Sites were separated into U_{40} (scoured at 40 mph) and S_{40} (unscoured at 40 mph) categories for the *t*-tests.

sites was generally higher than for U_{40} sites (Fig. 2, Table 2). Mean values of U_c ranged from 0.42 for one of the SW-wind U_{40} sites to 0.89 for one of the S_{40} SW-wind sites. U_{eff} of the U_{40} areas averaged 80% and 72% of S_{40} means for the NW and SW directions respectively. In contrast, mean values of I were essentially the same at S_{40} and U_{40} sites (Table 2). Hence, the difference in U_{eff} was caused primarily by the difference in the U_{mean} component.

Results of the *t*-tests indicate that the null hypotheses of equal U_{mean}, U_c and U_{eff} at the S_{40} and U_{40} sites would be rejected with an α of 0.01 or less (Table 2). The small difference in I between the S_{40} and U_{40} sites was not statistically significant even at the 0.10 level. Student *t* tests with the two directions combined showed differences in U_c and U_{eff} at the 0.0001 level of significance.

Values of U_{eff} for the U_{40} and S_{40} sites were 3.6 and 5.0 m s^{-1} for the NW wind and 4.1 and 6.3 m s^{-1} for the SW wind. Since effective winds of 6 m s^{-1} begin to result in human discomfort [13], the difference between the scoured and unscoured sites at a tunnel gradient speed of 18 m s^{-1} represented approximately the onset of human discomfort given the range of reference windspeeds under which the full-scale measurements were made.

There was a large overall range of average U_c for SW-wind S_{40} sites (Fig. 2), which may have been caused by unusual conditions at a few sites. The highest value occurred for a point at a street intersection between an 80-m-tall building on one corner and a 50-m-tall building on another. The lowest value of U_c occurred for a point 9 m in the lee of an 87-m-tall building. Although the scouring pattern surrounded this building on the scouring-pattern map used to select sites, the photograph from which the map was prepared revealed that the top of the building obscured full view of the site. There were no apparent large differences between the SW and NW directions in topography or general building plan upwind of the CBD, which might suggest a greater variability in U_c for one of the directions.

Several causes can be cited for the generally large scatter in U_c. First, airport windspeed is sampled for only a small portion of each hour, and thus reported airport windspeed may differ from the actual average speed for our 0.5-h periods. Second, atmospheric stability during measurements ranged from Pasquill Class D (neutral) to B (moderately unstable) and instability significantly increased windspeeds at pedestrian height. By assigning numerical values to the stability classes ($D=0$, $C=-1$, and $B=-2$), the simple correlation between stability and U_c was significant at the 0.001 level, with a coefficient (r) of 0.37. This effect was accounted for in the t-test analysis, because measurements were made simultaneously at the U_{40} and S_{40} sites. Third, in another analysis of the full-scale CBD wind data [14], even relatively small leafless deciduous trees, which were close to many of the sites, significantly influenced windspeed.

To estimate the potential magnitude of the effect of omitting measurements with the less-accurate high-speed anemometer scale in this analysis, these measurements were replaced with appropriate values of U_a and the analysis was re-run. The results differed negligibly from the original results, indicating that omission of the high-speed data did not affect the results within the resolution of the study.

3. Conclusions

Although the full-scale measurements reported here were made with relatively low-precision instruments, they are of interest because full-scale measurements for comparison with wind-tunnel simulation of pedestrian-level wind across urban areas are scarce, particularly for simulations with the plastic-pellet erosion technique. While there are potential problems with this simulation method, such as difficulty in producing an initial even distribution of the pellets, and the dependence of pellet movement on spacing [13], the simulation successfully differentiated points with pedestrian-level mean winds differing on average by 0.4 m s^{-1} (NW direction) and 0.8 m s^{-1} (SW direction).

Acknowledgements

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References

1 E.A. Arens, Designing for an acceptable wind environment, Transp. J., 107 (1981) 127-141.
2 F.H. Durgin and A.W. Chock, A brief review of pedestrian level winds. Rep. of Wright Brothers Memorial Wind Tunnel, M.I.T., Cambridge, MA, 1980, 42 pp.
3 A.R.J. Borges and J.A. Gil Saraiva, An erosion technique for assessing ground level winds, in J.E. Cermak (Ed.), Proc. 5th Int. Conf. on Wind Engineering, Fort Collins, CO, 1979, Pergamon, Oxford, 1980, Vol. 1, pp. 235-242.
4 W.J. Beranek and H. Van Koten, Visual techniques for the determination of wind environment, J. Ind. Aerodyn., 4 (1979) 295-306.
5 F.H. Durgin and M.C. Chan, A. wind tunnel study of pedestrian winds for the proposed Rowes Wharf Complex, Boston, Wright Brothers Memorial Wind Tunnel Rep. No. WBWT-TR 1201, M.I.T. Dept. of Aerodynamics and Astrophysics, Cambridge, MA, 1984, 181 pp.
6 R.E. Grip and F.H. Durgin, A wind tunnel study of pedestrian level winds in the vicinity of the proposed health sciences center, University of Minnesota, Minneapolis, Minnesota, Wright Brothers Memorial Wind Tunnel Rep. No. WBWT-TR 1144, M.I.T. Dept. of Aerodynamics and Astrophysics, Cambridge, MA, 1982, 191 pp.
7 A.W. Chock, Development and testing of a portable on-site ground wind data acquisition system, M.I.T., Dept. of Civil Eng., S.M. Thesis, February 1981, 85 pp.
8 M.L. Paget and F.W. Durgin, Flow visualization study of downtown Dayton, Wright Brothers Memorial Wind tunnel Rep. No. WBWT-TR 1143, M.I.T. Dept. of Aerodynamics and Astrophysics, Cambridge, MA, 1981, 7 pp.
9 J.A. Businger, J.C. Wyngaard, Y. Izumi and E.F. Bradley, Flux-profile relationships in the atmospheric boundary layer, J. Atmos. Sci., 28 (1971) 181-189.
10 F. Pasquill, The estimation of dispersion of windborne material, Meteorol. Mag., 90 (1961) 33-49.
11 D. Golder, Relations among stability parameters in the surface layer, Boundary-Layer Meteorol., 3 (1972) 47-58.
12 W.H. Melbourne, Criteria for environmental wind conditions, J. Ind. Aerodyn., 3 (1978) 241-249.
13 J.C.R. Hunt, E.C. Poulton and J.C. Mumford, The effects of wind on people; a new criteria based on wind tunnel experiments, Build. Environ., 2 (1976) 15-26.
14 G.M. Heisler and R.H. Grant, Predicting pedestrian-level winds in cities. in Preprints 18th Conf. on Agric. and For. Meteorol. and 8th Conf. on Biometeorol. and Aerobiol., West Lafayette, IN, 1987, Am. Meteorol. Soc., Boston, 1987, pp. 356-359.

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Isyumov, Nicholas

Full-scale studies of pedestrian winds: comparisons with wind tunnel and evaluation of human comfort

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Abstract

This paper provides an overview of a number of studies of pedestrian level winds carried out by engineering students at The University of Western Ontario (UWO) under the supervision of the author. These include full-scale measurements of wind speed on the UWO campus and in downtown London, Ontario. These studies have allowed comparisons with the results of wind tunnel model studies and have provided subjective data on the effects of wind on human comfort. Also discussed are experiments, where individuals were subjected to wind in a wind tunnel and their performance to do simple physical tasks was evaluated. Collectively, these students made valuable contributions to the subject of pedestrian level winds and their evaluation. Particular acknowledgements are made of the contributions of Messrs. Teng Leong Lim, John DeVito, Shane Maguire, Bob Levesque, Brad Wilson, Mike Cotton, Dave Emery, Hendrik Schuurmans, Frank Hochstenbach, Ron Kekich, Taymoor Azimi, Ms. Veronica Sun and Ms. Christine Strucchelli.

Index Keywords

Human engineering, Mechanical variables measurement, Pedestrian safety, Speed, Wind effects, Wind tunnels; Human comfort, Pedestrian winds, Speed measurement; Wind

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ENVIRONMENTAL WIND CHARACTERISTICS AROUND THE BASE OF A TALL BUILDING

- A COMPARISON BETWEEN MODEL TEST AND FULL SCALE EXPERIMENT -

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ABSTRACT

In order to obtain a better understanding of environmental wind characteristics, full-scale experiments were performed around the base of a tall building and model tests were also carried out in a boundary-layer wind tunnel.

This paper discusses the characteristics of environmental winds at pedestrian level around a tall building. Comparative studies of full-scale results with wind-tunnel results were made to determine the reliability of model tests by making some allowance for the correlation between them.

INTRODUCTION

Environmental winds around the bases of tall buildings have often caused troublesome problems(ref.1,3,6), such as unpleasant effects of increased wind velocity on people and damage to plants, trees and wooden framed residential houses, especially in Japan. A wind tunnel test is an effective way for estimating these effects.

Many model tests(ref.2,4) have been carried out in the boundary-layer wind tunnel to investigate environmental wind fields at ground levels. Some criteria (ref.3-8) for pedestrian comfort have already been proposed by use of statistical procedures in combination with wind tunnel results and local meteorogical data.

However, the results from a wind tunnel test may be different in detail from the real wind fields. There have been only a few full-scale experiments(ref.8-10) except for atmospheric observations of natural wind(ref.11,12) at heights of above 10 m. Although a few results have already explained some characteristics of the environmental winds, most measurements were performed at points higher than the pedestrian level and the surrounding terrain is different in each case.

Therefore, it is important to investigate the characteristics of environmental winds at pedestrian level. Full-scale experiments were performed in Honolulu, where moderately strong winds could always be expected. Model tests were also carried out in the boundary-layer wind tunnel.

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The purpose of this paper is to report on the results from a field experiment to cast some light on the characteristics of environmental winds. Comparative studies of full-scale results with those obtained from wind tunnel tests were performed to determine the reliability of model tests.

FULL SCALE EXPERIMENT

Experimental building

Environmental winds were measured at pedestrian levels around the Hawaiian Monarch Building in Honolulu, Hawaii, on Aug. 22, 1985.

This building is approximately 1 Km from Waikiki and surrounded with low-rise structures. This is a 44-story building which has a height to the eaves of 107 m and a tower plan dimension of 23 m x 23 m in addition to a lower portion of 35 m x 93 m.

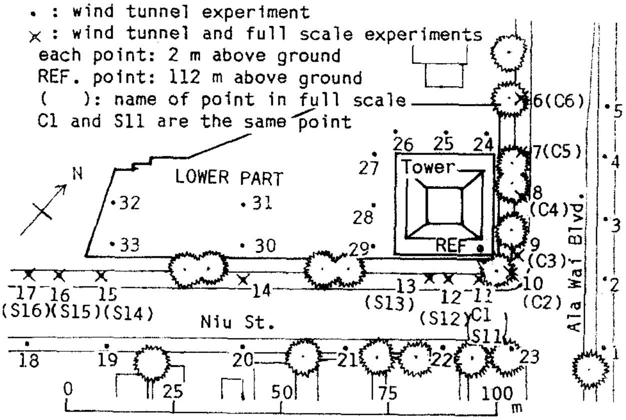


Fig.1 The measuring points in full scale and wind tunnel experiments

The trade winds usually approach this building over a large open area from a direction of 20°-90° in summer. The locations of measuring points are shown in Fig.1.

Measuring instruments

Seven three-cup anemometers and wind vanes were used. One anemometer and wind vane were set at the top of a 5 m mast on the roof (112 m above ground) for the reference wind. The others were relocated at pedestrian level.

Seven wind speeds and three wind directions including those at the reference point were simultaneously recorded on one magnetic tape. The other four wind vanes at pedestrian level were visually observed by assistants having transceivers with. The anemometer and the wind vane have time constants of about 0.8 s and 0.4 s respectively at 10 m/s of wind speed.

Experimental results

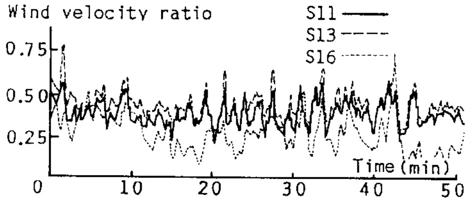
The wind velocity and direction at the reference point were almost 10 m/s and 40°-90° respectively throughout the experiments. The tape was mainly sampled at a scanning rate of 0.78 Hz.

Wind velocity ratio. Wind velocity ratio is defined as the ratio of wind velocity at pedestrian level to that at the reference point on the roof. The wind velocity ratios with running averages of 32, 160 and 800 s are shown in Fig.2(a),(b),(c) respectively. The values averaged over 10 min are listed in Table 1.

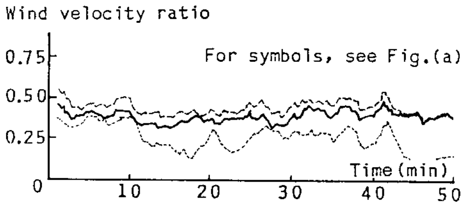
By connecting the velocity vector at each time one after another, the course of flow through the measuring period is shown in Fig.3. The mean wind velocity deduced from this vector drawing is given in Table 1, too.

Probability distribution. On the basis of about 45 min data, probability distributions of wind velocity ratios are shown in Fig.4(a). Distributions of wind direction are similarly shown in Fig.4(b). The dotted lines in this figure show the relative frequency obtained by assistants at regular intervals of 60 s. The most frequent wind directions are listed in Table 1.

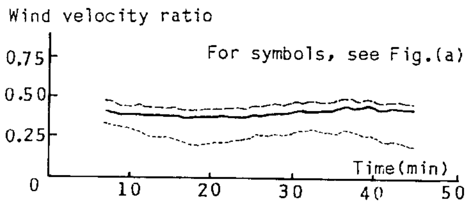
Turbulence. The variations of intensity of turbulence with averaging time are shown in Fig.5(a). Gust factors and peak factors are given in Fig.5(b),(c) respectively. Auto-correlations and power spectra of fluctuating wind velocity are given in Fig.6(a),(b) and cross-correlations, root-coherence and phase are given in Fig.6(c),(d) and (e), respectively. These figures are normalized by use of mean wind velocity U at each point and building width of L=23 m.



(a) Averaging time = 32 s



(b) Averaging time = 160 s



(c) Averaging time = 800 s

Fig.2 Wind velocity ratio with running average (Case 2)

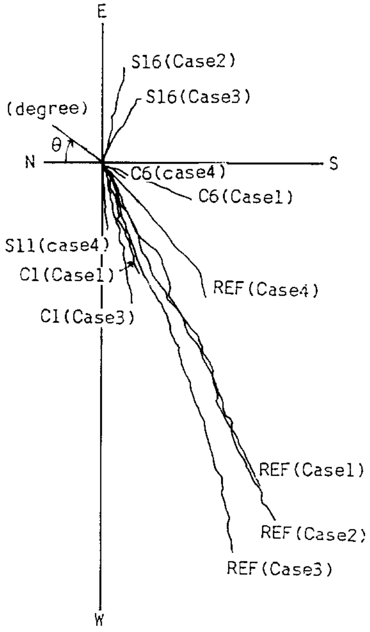


Fig.3 The winds in terms of vectors

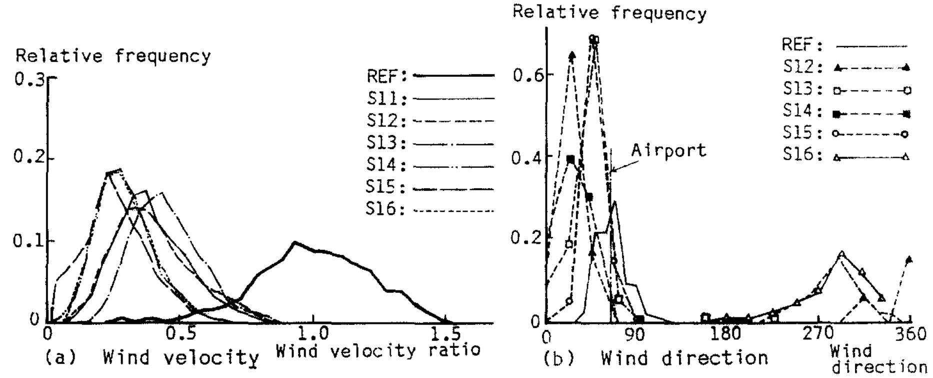


Fig.4 Probability distribution (Case2)

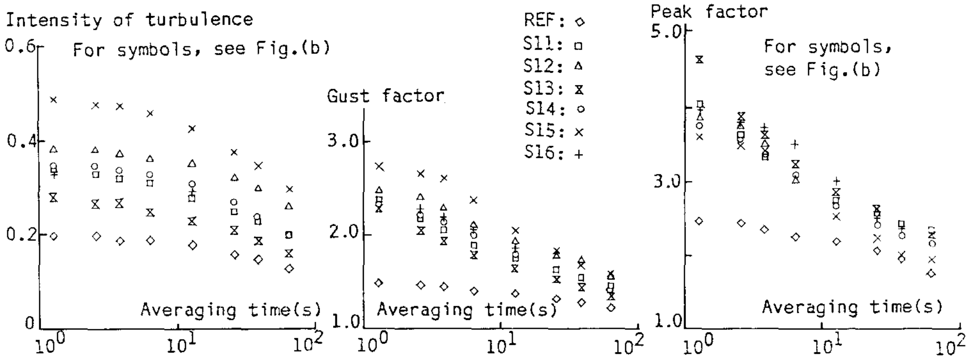
The outlines of full scale experiment are listed in Table 1.

Table 1

Outline of full scale experiment

Case	Point	Wind Direction (degree)	Wind Velocity Mean (m/s)	Wind Velocity Max (m/s)	Wind Velocity Ratio	Intensity of Turbulence	Gust Factor	Integral Scale of Turbulence	Honolulu Wind Velocity (m/s)	Airport Wind Direction (degree)
	REF	59 [63]	8.6	15.7	1.00 [1.00]	0.21	1.6	436		
	C1	79-90 [78]	3.4	9.1	0.40 [0.38]	0.30	2.0	162		
	C2	(315)	2.7	8.5	0.31	0.40	2.3	120		60
1	C3	(315)	3.0	7.2	0.35	0.32	2.0	74	8.2	|
	C4	(113,270)	2.0	6.0	0.23	0.47	2.8	23		70
	C5	(135)	2.2	6.5	0.26	0.53	2.7	49		
	C6	20 [23]	2.6	6.1	0.30 [0.26]	0.33	2.1	65		
	REF	70 [64]	10.0	16.8	1.00 [1.00]	0.20	1.5	239		
	S11	--	3.9	10.6	0.39	0.34	2.4	55		
	S12	(23)	4.0	11.1	0.40	0.38	2.5	87	7.2	50
2	S13	(45)	4.4	12.7	0.44	0.28	2.3	58	|	|
	S14	(23)	2.8	7.6	0.28	0.35	2.3	49	8.7	80
	S15	(45)	2.4	7.6	0.24	0.49	2.8	65		
	S16	290 [284]	2.9	7.3	0.29 [0.25]	0.33	2.3	61		
	REF	70 [70]	10.6	16.3	1.00 [1.00]	0.18	1.5	204		
	C1	79-90 [77]	3.8	9.8	0.36 [0.35]	0.41	2.5	90		
	C2	(315)	4.3	9.7	0.41	0.34	2.2	101	7.2	70
3	C3	(315)	3.4	8.9	0.32	0.39	2.5	82	|	|
	S14	(23-45)	3.2	7.4	0.30	0.32	2.0	92	8.2	90
	S15	(45)	2.9	7.8	0.27	0.43	2.4	105		
	S16	300 [300]	2.2	7.9	0.21 [0.19]	0.47	2.7	54		
	REF	51 [50]	10.0	13.4	1.00 [1.00]	0.13	1.3	355		
	S11	89 [87]	4.1	7.9	0.41 [0.41]	0.22	1.9	85		
	S12	(45)	3.5	7.9	0.35	0.34	2.1	43	7.7	
4	S13	(45)	4.2	8.3	0.42	0.26	2.0	40	|	60
	C4	(225)	1.9	5.2	0.19	0.48	2.7	32	8.2	
	C5	(135)	1.6	5.4	0.16	0.56	2.9	20		
	C6	28-37 [33]	2.2	5.7	0.22 [0.14]	0.34	2.2	50		

Note
1 ( ) means the most frequent wind direction recorded by assistants.
2 [ ] means the linearized wind direction and velocity in terms of the vector.
3 The data for Honolulu Airport are the hourly readings closest to each run.
4 Gust factor and intensity of turbulence are from averaging time of 1.28 s.



(a) Intensity of turbulence (b) Gust factor (c) Peak Factor

Fig.5 Variations of intensity of turbulence, gust factor and peak factor

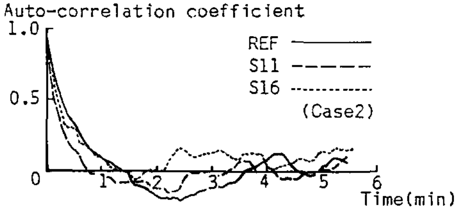


Fig.6(a) Auto-correlation coefficient

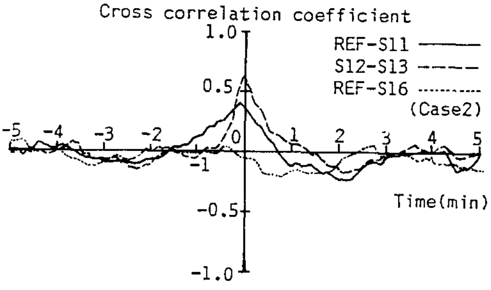


Fig.6(c) Cross-correlation coefficient

WIND TUNNEL TEST

Model and wind flow

The test was performed on a 1/300-scale model of an area 450 m in diameter in the Boundary Layer Wind Tunnel at the Disaster Prevention Reseach Institute, Kyoto Univ..

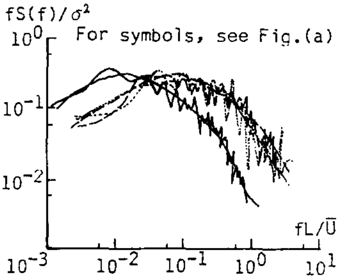


Fig.6(b) Power spectra (Case2)

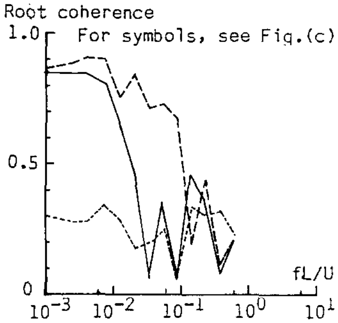


Fig.6(d) Root coherence (Case2)

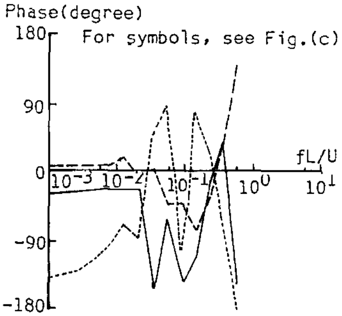


Fig.6(e) Phase(Case2)

The roughness block were used to simulate the approach flow. Fig.7 shows the characteristics of approach flow in wind tunnel. The constant wind velocity above the boundary layer thickness was set at about 10 m/s. The measuring points are also shown in Fig.1.

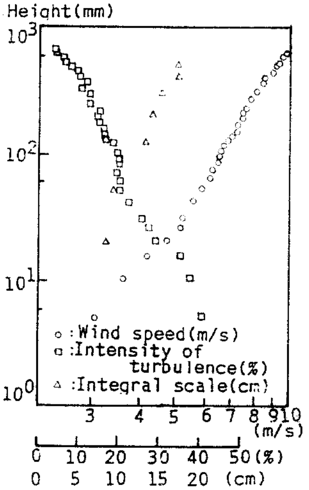
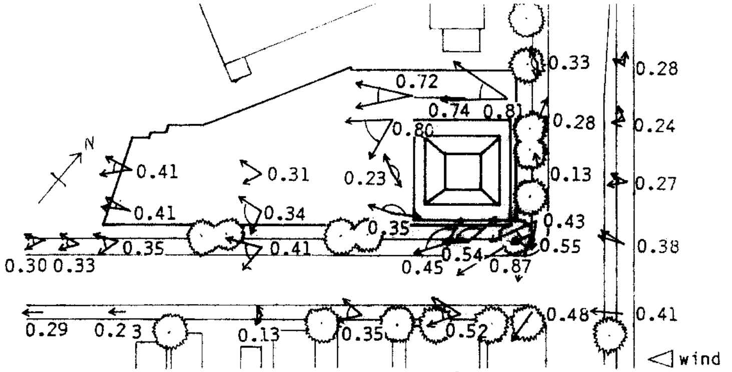


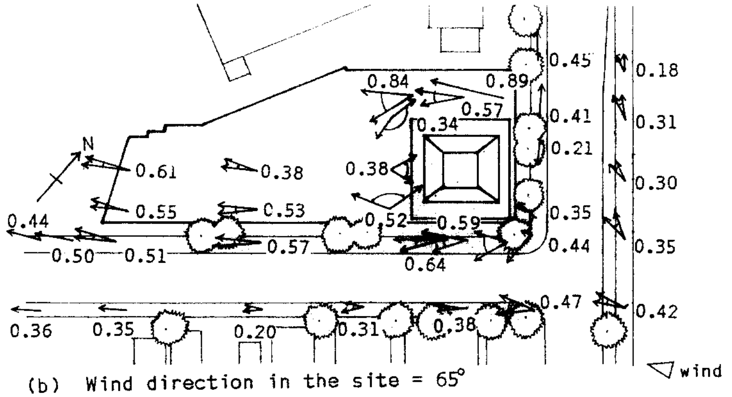
Fig.7 Characteristics of approach fow in wind tunnel

Measuring instruments

The measurements of wind fields were made by use of a hot-wire anemometer connected to a magnetic recorder. The velocities were sampled at a scanning rate of 500 Hz during the whole measuring period of about 10 s. The wind direction at each point was obtained via pictures of dandelion seeds taken right over the model. Wind directions for model tests were limited to the predominant



(a) Wind direction in the site = 50°



(b) Wind direction in the site = 65°

Fig.8 Wind velocity ratio and wind direction ones in full scale experiments.

Test results

The wind velocity ratio was similarly defined as that in full scale experiments. Fig.8(a),(b) show the wind velocity ratios and the variations of wind directions.

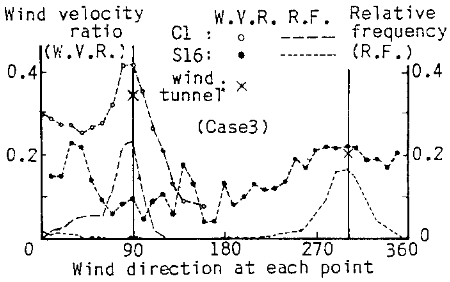


Fig.9 Variation of wind velocity and relative frequency with wind direction at each point

COMPARISON OF RESULTS

Wind velocity ratio

The wind velocity ratio and wind direction deduced from the vector drawing are nearly close to those from the probability distribution except for the wind of lower velocity.

The variation of wind velocity ratio with wind direction at two points is shown in Fig.9 together with the relative frequency of wind direction. The most frequent wind direction at the point C1 is coincident with that where the wind velocity ratio has a peak value. The wind velocity ratio at the point S16 has two peaks at 30° and 300° in spite of rare probability of wind direction at 30°.

The wind velocity ratios in model test seem to be in accordance with those in full scale with the most frquent wind direction.

Fig.10 shows the variations of wind velocity ratios, averaged over 10 min, with distance from the windward frontal point. The ratio shows an increase beyond half the width of building when the wind is somewhat parallel to the measuring points. The ratio shows a decrease at the mid-point and a rapid increase beyond it when the wind is somewhat across the measuring points.

On the other hand, the model results show rather larger values compared with those in full scale except for the wind-

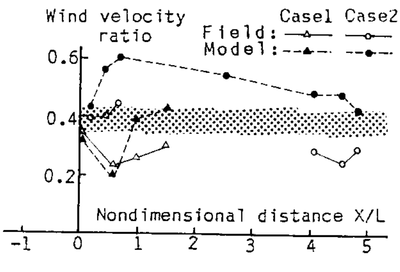


Fig.10 Variation of wind velocity ratio with distance from windward point

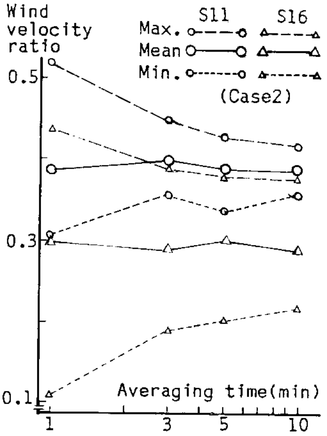


Fig.11 Variation of wind velocity ratio with averaging time

ward frontal points.

Supposing the terrain has a wind profile in which its power index is about 1/4-1/5, whose velocities at the height are indicated by shading, the increased wind velocity appears at the leeward side of building and the decreased wind velocity appears at the front of building.

The variation of wind velocity ratios with averaging time is shown in Fig.11. As illustrated in Fig.2, the maximum and minimum values show a convergent tendency toward a mean value in proportion to the averaging time, whereas the mean values are almost constant for the periods of these averaging times.

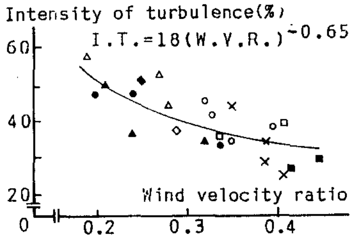


Fig.12 Relarion between intensity of turbulence and wind velocity

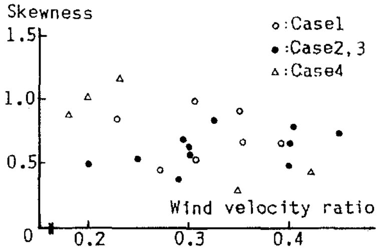


Fig.13(a) Variation of skewness in velocity distribution with wind velocity ratio

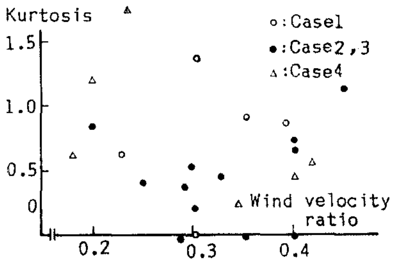


Fig.13(b) Variation of kurtosis in velocity distribution with wind velocity ratio

Turbulence of wind velocity

Both intensity of turbulence and gust factor decrease with averaging time as shown in Fig.5. The decrements of these quantities change at the averaging time of about 10 s, corresponding to the scale length where the normalized power spectra begin to decrease suddenly in the higher frequency ranges.

The relation between intensity of turbulence and mean wind velocity ratio is shown in Fig.12. The regression line indicates the expected trend that the intensity of turbulence decreases slowly with the increase of mean wind velocity. Both skewness and kurtosis in probability distribution of wind velocity ratio are given in Fig.13(a),(b).

The skewness decreases slightly in proportion to the wind velocity ratio, although the kurtosis is too scattered to obtain a clear trend from these results.

Cross correlation

Based on the cross correlation coefficient, the convection velocity is deduced to be about 7.5 m/s between the reference point on the roof and the windward frontal point C1 and 5.3 m/s between points S11 and S13, respectively. The turbulence of wind velocity could be transmitted from the roof to the pedestrian level in 15 s at least. Hundreds of seconds will be necessary for the wind to form the quasi-steady flow pattern around the base of building. Fig.2(b) shows a good correspondence and Fig.2(c) shows rather steady values. However, it should be noted that the turbulence of this scale has lower values in power spectra.

Comparison of model and full-scale test

Fig.14 shows a comparison of model test results with those averaged over 1 min in full-scale as to mean wind velocity ratio. In this figure, symbols mean the max. and min. values. The results from model tests are slightly larger than those from full-scale tests. The linear regression line is drawn as a dot-dash line. The slope is 1.43 and the correlation coefficient is 0.79, which are nearly the same as for the mean wind velocity averaged over 10 min.

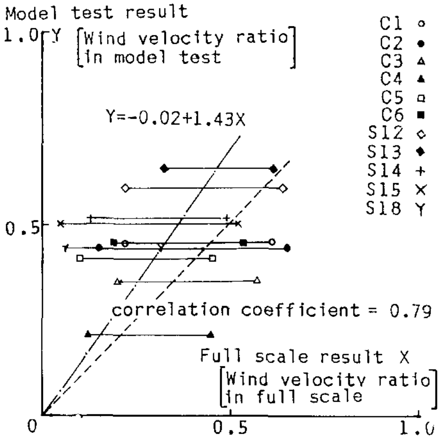


Fig.14 Comparison of model test and full scale as to the wind velocity ratio

Comparing the wind directions in wind tunnel with those in full scale, both seem to have a similar trends for the leeward points and to be different from each other at the windward points.

CONCLUSION

The mean wind velocity and the wind direction could be obtained from the usual methods of probability distribution except for winds of relatively lower velocity with variable wind direction.

With regard to wind velocity ratio, the wind tunnel model test provides larger values than those averaged over 1-10 min in the full-scale tests and the correlation coefficient is almost 0.8.

The integral scale of wind is in the order of a few hundred meters at the roof of the building and varies from 160 to 20 meters at the pedestrian level. The convection velocity of turbulence is below 10 m/s between the roof and the windward frontal point at pedestrian level.

The intensity of turbulence decreases in proportion to wind velocity ratio. The skewness in probability distribution of velocity also decreases in proportion to the wind velocity ratio. Then, the probability of wind velocity may not be a Gaussian distribution especially in lower wind velocity.

Comparatively larger wind velocity ratios appear for only a few wind directions at the leeward point in the full-scale tests, but this does not seem to appear in the wind tunnel model. If this phenomenon could cause pedestrian discomfort, this will be a notable problem to be solved in the future.

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REFERENCES

1 H.Ishizaki, Recent developments and trends: local wind environment, Proc. 5th Intern. Conf. Wind Eng., 1979, pp.223-224.

2 W.J.Beranek, General rules for the determination of wind environment, Proc. 5th Intern. Conf. Wind Eng., 1979, pp.225-234.

3 J.Gandemer, Wind environment around building: Aerodynamic concepts, Proc. 4th Intern. Conf. Wind Effects on Buildings and Structures, 1975, pp.423-432.

4 J.Gandemer, Aerodynamic studies of built-up areas made by C.S.T.B. at Nantes, France, J. Industrial Aerodynamics, 3, 1978, pp.227-240.

5 W.H.Melbourne, Criteria for environmental wind conditions, J. Industrial Aerodynamics, 3, 1978, pp.241-249.

6 N.Isyumov and A.G.Davenport, The ground level wind environment in built-up areas, Proc. 4th Intern. Conf. Wind Effects on Building and Structures, 1975, pp.403-422.

7 S.Murakami, K.Uehara and K.Deguchi, Wind effects on pedestrians: New criteria based on outdoor observation of over 200 persons, Proc. 5th Intern. Conf. Wind Eng. 1979, pp.277-289.

8 P.R.Sparks and J.Elzebda, A comparison of pedestrian comfort criteria applied to a city center, J. Wind Eng. and Industrial Aerodynamics, 15, 1983, pp.123-132.

9 M.Shiotani, Y.Iwatani and N.Yamada, Wind flow turbulence in a gusty area around a high-rise building, Colloque Designing with the Wind, Nantes, 1981, pp.II-3-1-II-3-13.

10 S.Murakami and K.Fujii, Turbulence characteristics of wind flow at ground level in built-up area, J. Wind Eng. and Industrial Aerodynamics, 15, 1983, pp.133-144.

11 A.J.Bowen, Full scale measurements of the atmospheric turbulence over two escarpments, Proc. 5th Intern. Conf. Wind Eng., pp.161-172.

12 S.O.Hansen and E.G.Sorensen, The Aylesbury experiment. Comparison of model and full-scale tests, J. Wind Eng. and Industrial Aerodynamics, 22, 1986, pp.1-22.

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THE GROUND LEVEL WIND ENVIRONMENT AROUND THE SHEFFIELD UNIVERSITY ARTS TOWER*

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Summary

The Arts Tower forecourt at the University of Sheffield is a large open area surrounded on the east and west sides by low rise buildings and on the north side by a high-rise tower block. Pedestrian access to the tower block is across the forecourt and instances of severe personal discomfort due to wind effects are common in this area during the period from September to March of each year. An investigation of the ground level wind environment has been undertaken at both model scale and full scale and the existing situation has been defined.

The use of various combinations of entrance pavilions, roofs and fences have been studied in a wind tunnel in an attempt to formulate a design which would alleviate the area's present problems of personal discomfort which are induced by wind effects.

1. Introduction

The effect of isolated high rise buildings in urban areas in producing an unacceptable ground level wind environment is well known and its causes have by now been thoroughly documented [1]. Basically the physical situation is one in which the wind at higher levels, which normally flows over the average rooftop height, strikes the exposed upper storeys of a high-rise block and is deflected to ground level forming a vortex. This vortex has its axis running along the front face of the building and down either side. It is in these areas that wind speeds can exceed those normally defined as being within the acceptable level of human comfort. This situation is made significantly worse in winter time, the time of strong winds, since the air temperature is lower and there is frequently the combined occurrence of wind and rain.

The Western Bank area of Sheffield University suffers from this problem of unacceptable ground level wind speeds due to the existence of the Arts Tower, see Fig. 1. The basic problem is worse in this case for the following two reasons. The first is that the main entrance, and hence pedestrian access

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*Paper presented at the 3rd Colloquium on Industrial Aerodynamics, Aachen, June 14–16, 1978.

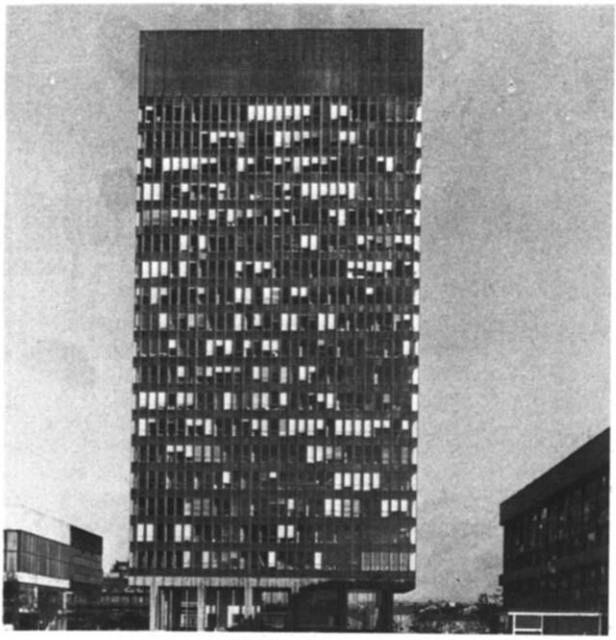

Fig. 1. The Arts Tower.

route, is at the centre of the wider side of the plan form and thus in the immediate vicinity of the front part of the vortex flow. The second problem is caused by the siting of the Library to one side of the Arts Tower in such a position as to trap the side arm of the vortex and accelerate the existing high winds. This side passage is also an important pedestrian access route. The general disposition of buildings around the Arts Tower forecourt is shown in Fig. 2. The roof heights are as follows: Arts Tower 78 m, Library 10 m, Chemistry 10 m, Biology Building (North) 18 m and Biology Block (South) 32 m. There is a pedestrian bridge at first floor level between the Arts Tower and the Library, beneath which there is a headroom of 5 m.

In an attempt to alleviate this situation a proposal has been put forward for the construction of an entrance pavilion connected to the main building by a short passageway. The aim of the study reported here was to examine the effect of this addition to the site, on the wind velocities around pedestrian access routes. Variations in the form of this entrance pavilion have also been studied, in addition to the use of screens.

2. Full-scale tests

A full-scale test has been conducted in order to determine the variation of mean wind speeds over the Tower Court area. This test was conducted by undergraduate students operating in pairs, reading small cup anemometers located at 2 m above ground level. The anemometers were read at intervals

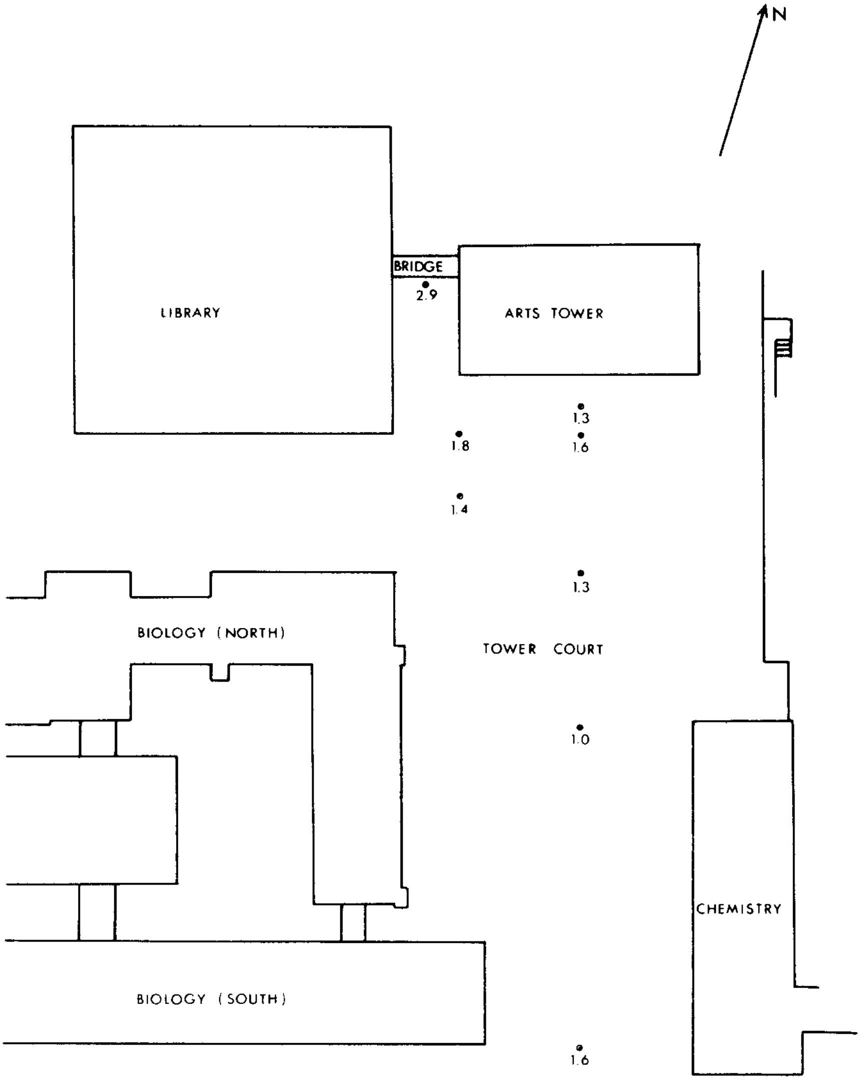

Fig. 2. Full-scale tests: Mean velocity ratios.

of 15 seconds for a period of one hour, at a number of points on the site simultaneously. The wind direction was southerly such that the wind blew normal to the wide face of the building.

The results of this test are shown in Fig. 2 where the mean speeds across the Tower Court have been normalized with respect to the speed at the centre of the Court, i.e. outside the region of influence of the Tower's vortex The figure clearly shows the higher wind speeds associated with the front and side arms of the vortex and highlights the flow acceleration beneath the bridge joining the Library and Arts Tower. This pattern of wind speed variation correlates very well with the subjective assessments of the wind environment built up by the authors over a long period of use of the Tower Court.

The wind storm data for Sheffield has also been analysed [2], and it has been shown that over the period 1962–1976 there were an average of 21 storms per annum with wind speeds exceeding 10 m/s for a minimum period of 20 minutes, measured at the Weston Park meteorological station. This meteorological station is about 0.5 km from the Tower Court and for southerly winds the ratio of the station mean wind speed to the mean wind speed at the Tower Court centre is approximately 1.5. Hence the mean speed under the bridge between the Library and the Arts Tower will exceed 19 m/s on average on 21 occasions every year for a period of at least 20 minutes on each occasion. This situation would be regarded as unacceptable by most wind effects criteria [1].

3. Wind tunnel tests

A series of wind tunnel tests have been conducted in order to determine the likely effect of alterations and additions to the Arts Tower, proposed for the benefit of reducing the ground level wind speeds. A test on the existing building layout was performed first in order that a comparison could be made with the full scale results to check the adequacy of the modelling technique.

The wind tunnel tests were carried out in the Department of Building Science 1.1 × 0.8 m wind tunnel using an accelerated boundary layer growth technique to simulate the flow properties of the atmospheric wind over urban terrain. The tests included both surface paint flow visualization and velocity measurements. The surface paint flow visualization technique used was similar to that described by Yu [3]. The velocity measurements were made with a Prosser Scientific Instruments AVM500 unshielded thermistor probe anemometer.

The results of the wind tunnel test programme are presented in Figs. 3–8. The shaded areas in Figs. 3–6 indicate the region of ground level flow disturbance caused by vortex, as shown by the surface paint visualization technique. The mean velocities in all the Figures have been normalized with respect to that at the centre of the Tower Court.

Only one flow direction has been tested, this being a southerly wind blowing normal to the south face of the Arts Tower, on which the entrance is situated. This condition is the one which will produce the most severe environmental wind conditions.

4. Discussion of wind tunnel tests

4.1 Existing building layout

Figure 3 shows the wind pattern at a height of 2 m for the building layout as it exists at present. The comparison with the velocity ratios for the full-

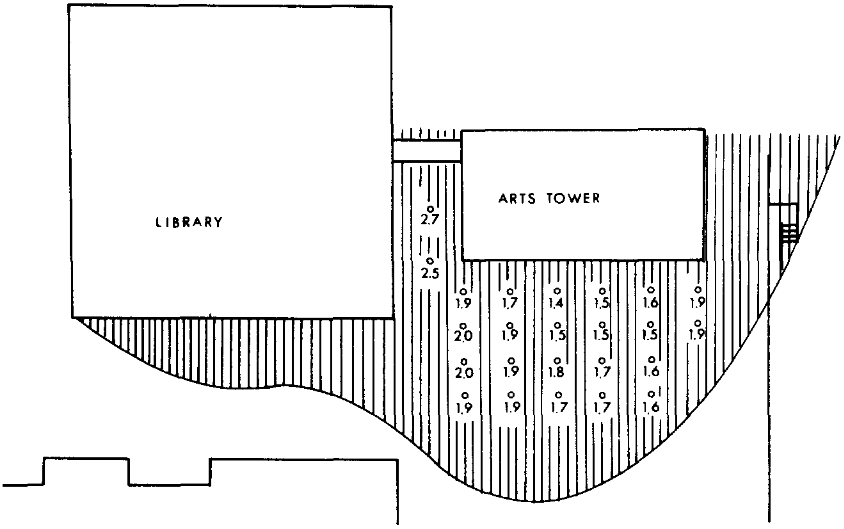

Fig. 3. Wind tunnel tests: Mean velocity ratios, existing building layout.

scale tests, Fig. 2, is good, both directly in front of the Arts Tower and in the side passage beneath the link bridge. This agreement between the full scale and model tests indicates that the modelling techniques were satisfactory.

The report by Penwarden and Wise [1] includes an approximate method for estimating the velocity ratio between the undisturbed velocity at the roof height level and the velocity near ground level in the accelerated side flow region, for an otherwise isolated tower block. If an incident power-law velocity profile with an exponent of 0.30 is assumed, the comparable velocity ratio for the situation shown in Fig. 3, for the side passage area becomes 2.2. Although this is a lower figure than either of the present tests gives, 2.9 for the full-scale tests and 2.7 for the model tests, it is considered to be acceptable since no allowance for the presence of the Library or the link bridge can be made, both of which will tend to increase the local flow speed.

4.2 The effect of an entrance pavilion

It has been shown elsewhere [4] that one of the most successful methods of eliminating pedestrian discomfort in front of tall buildings is to provide a low rise extension in the form of an entrance pavilion. The main effect of such an addition, is that the front of the base vortex now lies on top of the pavilion and permits more acceptable entry conditions to the building complex as a whole. Two such entrance pavilions, 8 m in height, were fitted to the front of the Arts Tower and the resulting velocity ratios were measured, Figs. 4 and 5. It is worth noting here that the entrance pavilions were required to meet certain architectural specifications and hence their form is more limited than aerodynamic reasons might have dictated.

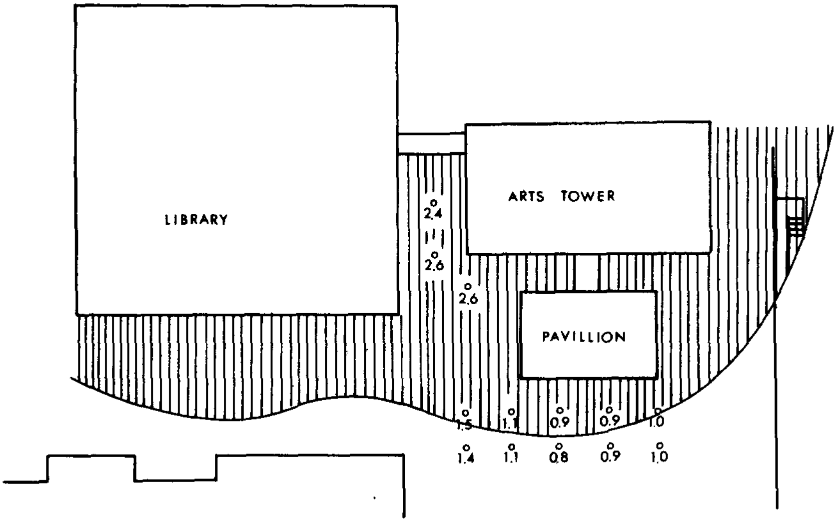

Fig. 4. Small entrance pavilion.

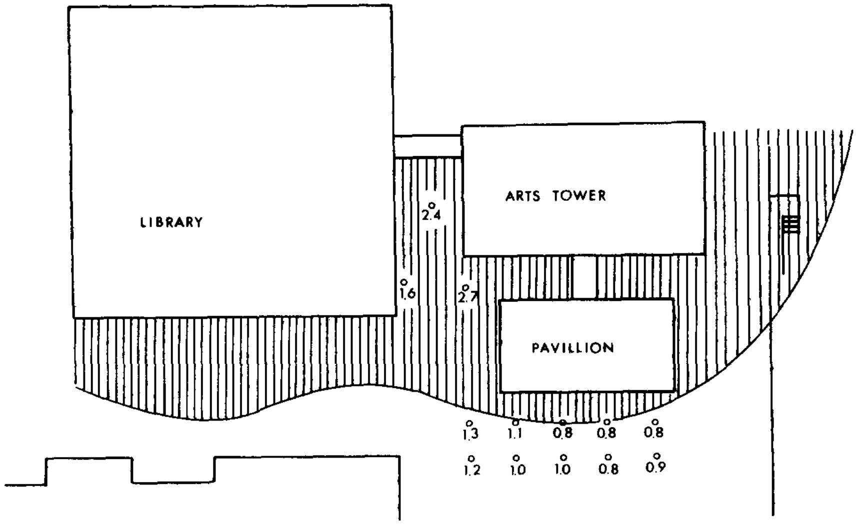

Fig. 5. Large entrance pavilion.

The effect of the entrance pavilions in reducing the wind speeds in front of the Arts Tower is quite clear from the figures. The speed ratios along the front pedestrian access route are reduced from values of 1.5 to 1.9 in the present situation to values of 1.1 to 0.8 when the pavilion is fitted. However, Figs. 4 and 5 show that the speed ratios in the side passage are relatively unaffected by the presence of a front pavilion indicating that the side arm of the vortex remains at ground level and still passes beneath the bridge.

In order to attempt to reduce these side flow velocities a roof was fitted over the gap between the entrance pavilion and the Arts Tower, since it was initially thought that the small cavity between the two buildings might be responsible for the low level of the side arms of the base vortex. The results of this addition to the smaller of the two entrance pavilions is shown in Figure 6, where it can be seen that only a small reduction in the side passage speed ratios has been effected, i.e. from 2.4 to 2.3.

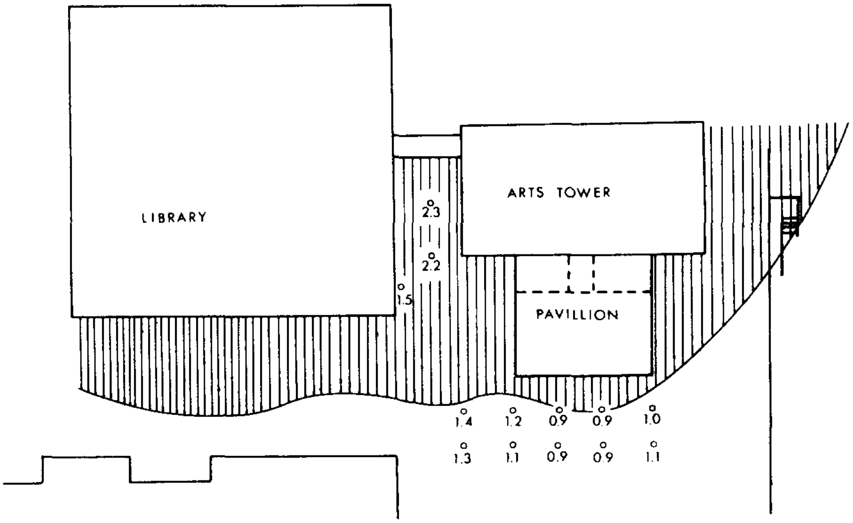

Fig. 6. Partial roof behind small entrance pavilion.

4.3 *The use of fences*

The use of porous screens for reducing flow speeds in the side arms of the base vortex around a high rise building has been suggested previously by Valensi [5] in connection with a housing development in Avignon. In this case vegetation screens were placed immediately adjacent to the building at an angle of 150° to its longitudinal axis and were shown to produce significant reductions in the side flow velocities. Since none of the pavilion/roof layouts have been shown to produce a sufficient reduction in flow speeds in the side passage in the present tests, it was considered appropriate to look at the effect of porous screens across the entrance. The screens had a solidity of 50% and were 3 m high, their height being limited by architectural considerations.

The effect of these porous screens on the side passage flow speed ratios are shown in Figs. 7 and 8, for two different screen layouts. It is rather disappointing, particularly in view of Valensi's results, to see that in the present case the screens have virtually no effect on the flow speeds in the passage. It is suggested that the vortex flow experiences a pronounced downward

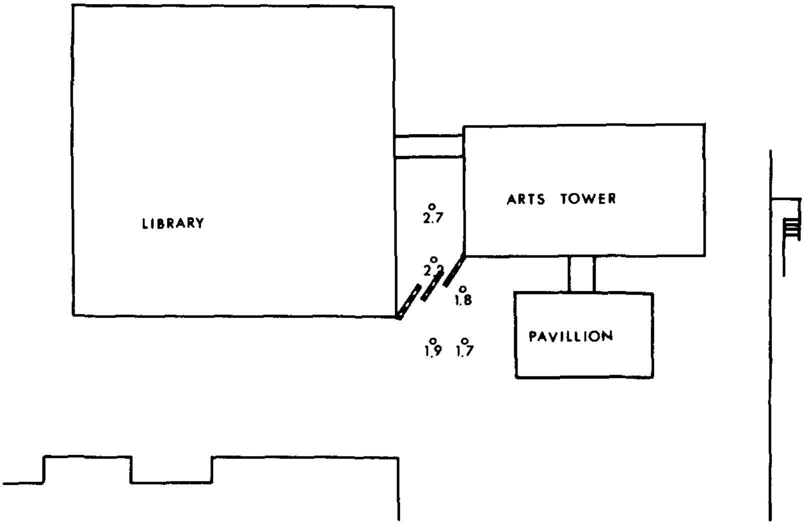

Fig. 7. Fence arrangement No. 1.

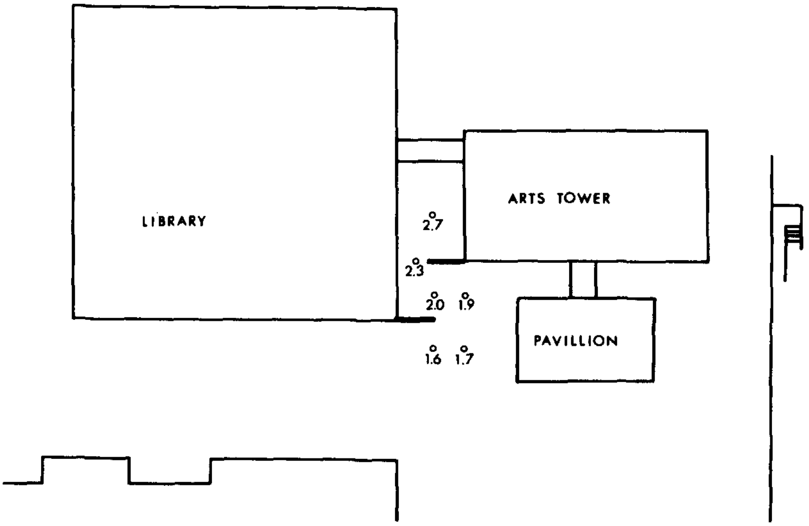

Fig. 8. Fence arrangement No. 2.

movement as it turns the s.w. corner of the Tower, from the front vortex region on the pavilion roof, 8 m high, in order to pass beneath the link bridge, 5 m headroom. If this is the case then it would seem plausible that fences limited to 3 m in height would not present a sufficient obstacle to break up the side vortex flow. It is suggested that a significant increase in the fence heights would be necessary to produce the required reductions in the side flow wind speeds.

5. Conclusions

1. Full-scale tests on the wind environment of the Arts Tower forecourt have indicated significant increases in wind speed at the front of the building and in the side passage beneath the link bridge joining the Arts Tower to the Library at first floor level. These increases in wind speed are considered to be caused by the presence of a ground level vortex common to tall buildings.
2. A comparison between the results of full-scale tests and wind tunnel model tests have indicated that an acceptable modelling technique has been formulated.
3. The construction of an entrance pavilion to the front of the Tower has been shown to produce significant reductions in flow speeds on the main pedestrian access to the building, but to have little effect on flow speeds in the side passage.
4. The use of porous screens of limited height across the entrance to the passage has been shown to have no effect on the flow speeds therein.
5. Other aerodynamic solutions to the problem of reducing the high wind speeds in the side passage, were considered to be architecturally undesirable. These other solutions include higher fences across the passage entrance, a roof over the passage linking up with the entrance pavilion roof and blocking off the open area beneath the link bridge.

References

1 A. Penwarden and A. Wise, Wind Environment Around Buildings, Building Research Establishment, 1975, Report H.M.S.O.
2 B.E. Lee, Extreme wind data and building design, Weather, Roy. Met. Soc., 33(11) (1978) 416—422.
3 C. Yu, Flow Around a Square Block, M.Sc. Thesis, Dept. Aero. Engng., Imperial College, London, 1975.
4 A. Wise and A. Penwarden, Wind environment around large buildings, Symp. on External Flows, Bristol University, 1972, paper J.
5 J. Valensi, Von Karman Inst. for Fluid Dynamics Belgium, Lecture Series 45, 1972.

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Full scale measurement of wind speeds in an inner city

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Abstract

Continuous full scale wind speed measurements on an inner city footpath are being undertaken in order to evaluate wind tunnel methods of predicting the street level wind environment. Initial results are analysed and some comparisons with results from a 1:200 scale wind tunnel test are presented.

1. INTRODUCTION

The construction of tall buildings significantly alters the street level wind environment and many city authorities require wind tunnel testing of new developments to assess their impact on the local wind environment. Street level wind speeds are of concern for two reasons. Firstly, high gust wind speeds unbalance pedestrians. This may lead to serious injury or death, especially if the person is blown into the path of traffic. Secondly, persistent lower strength winds causing a wind environment that is perceived as unpleasant can result in social and economic losses as people will avoid such areas. This is particularly relevant in outdoor entertainment, shopping or eating areas.

The basic flow mechanisms leading to wind environment problems at street level are reasonably well understood [1],[2]. However, the complex nature of flow in an inner city environment means that in general a wind tunnel test is required to assess the local wind environment. Then should problems be identified it is possible to estimate their significance and if necessary evaluate measures for improvement.

For some two decades wind tunnel tests have been a very useful tool in assessing the wind environment in cities, and limited comparisons between full scale and wind tunnel tests [3 - 10] have reported reasonable agreement for flow patterns and velocities. However, as Grant et al. [10] suggest there is still a scarcity of validations of wind tunnel tests, particular ly in respect of predictions of the long-term statistics of the street level wind climate.

This paper describes a project currently underway which specifically aims to obtain long-term street level wind data with the ultimate goal being to evaluate the performance of the current method of assessing the local wind environment.

2. WIND ENVIRONMENT ASSESSMENT

A procedure using wind tunnel tests to establish and consequently assess the wind environment around a building is described in [11]. At the outset, the statistical wind climate for the site of the building development must be established from long-term wind records, usually those of a nearby meteorological station.

Typically, mean wind speed records are fitted to a directional Weibull probability distribution of the form,

$$P(v>V, \theta)=A(\theta)\exp[-(V/C(\theta))^{K(\theta)}] \quad (1)$$

where $P(v>V,\theta)$ is the probability of exceedance of the mean wind speed V from wind direction θ, and $A(\theta)$, $C(\theta)$ and $K(\theta)$ are the Weibull parameters. Because most buildings are occupied during working hours, the probability analysis is usually restricted to daylight hour records.

A wind tunnel test is then undertaken to measure the mean and gust wind speeds at various sites around the building development for the complete range of wind directions. These local velocities are normally expressed as a ratio of a reference wind tunnel velocity. Using these velocity ratios, an atmospheric boundary layer model [12] and the statistical wind climate obtained earlier, the directional probability distribution of mean and gust wind speeds at each site can be predicted.

Melbourne [13] has compared various environmental wind speed criteria and proposed a range of wind speeds and probabilities of occurrence for various activities. An assessment of the wind environment around the building can then be made using these criteria.

This is a well established procedure, but it remains one that has had very little validation through full scale experimentation.

3. PREVIOUS FULL SCALE STUDIES

Isyumov and Davenport [3] report full scale measurements made at Commerce Court Plaza in Toronto, where a 240m high building significantly influences the street level wind environment. Full scale mean wind speed and direction measurements were made at seven locations for a period of only two weeks. The reference wind speed was taken some 46m above the tall building. A 1:400 scale model was tested in a boundary layer wind tunnel and comparison of velocity ratios, local velocity/reference velocity for model and full scale revealed some 'noticeable differences'. However, the authors concluded that with the many uncertainties in the full scale measurements the overall agreement was reasonable. No attempt was made to establish the probability distribution of street level wind speeds.

Lee and Hussain [4] report a comparison between model and full scale flows around an isolated tall building. Dye [5] reports a similar investigation again concluding that the model was able to predict windy areas reasonably well but that much more full scale data should be obtained. In each case the period of data collection was short.

Perhaps the most comprehensive program of full scale wind speed measurements has been undertaken in Japan [6-9]. In particular, Sanada et al. [7] report the results of some three years of continuous measurement of street level wind speeds around the Shinjuku area of Tokyo. Here, street level wind speeds were referenced to measurements at the top of one of six tall buildings in the neighborhood.

Wind tunnel tests were also conducted and reasonable agreement between velocity ratios (local velocity/reference velocity) for model and full scale was found. Indeed, the probability distributions of street level wind speed were predicted with encouraging results using the model scale velocity ratios and the probability distribution of the full scale reference wind speed. Wind tunnel tests were thus demonstrated as a relatively effective means of assessing wind environment.

However, there remains the problem of the reliability of wind environment assessments when the reference wind climate position is located at some distance from the site under consideration, as is commonly the case in such studies. This is the main consideration of the present investigation.

4. PRESENT FULL SCALE STUDY

4.1. Background

Buildings need not be excessively tall to produce problems at street level; more often it is the exposure of the building to prevailing winds that is of most significance. To be specific, the Central Business District (CBD) of Brisbane, the third largest city in Australia, is situated in a large loop of the Brisbane River. Within the CBD high rise development has occurred with buildings ranging in height up to 150m. Across the river there remains generally low rise residential buildings extending many kilometres in all directions. The river forms a natural barrier to the normal cascade of building heights from the city centre and those buildings on the river front are particularly exposed to winds from the east and the southwest. As it happens these are the predominant wind directions in summer and winter respectively. A locality plan is shown in Figure 1.

Although wind tunnel tests on newer buildings in the CBD have been undertaken as required by the City Council, problems associated with older buildings and the general river front exposure of the CBD have led to the development of several uncomfortably windy sites.

For a period of five years wind speeds on inner city streets in Brisane were monitored on an adhoc basis by undergraduate students of the Department of Civil Engineering using hand held anemometers. Their aim was to identify and obtain a feel for the magnitude of the wind environment problem. On at least one occasion a gust speed of 20m/s was measured which is approaching dangerous levels [13]. In April 1990 a permanent anemometer station was established at one of the problem sites on a busy footpath in the city center. A plan of the city region where the station is located is shown in Figure 2.

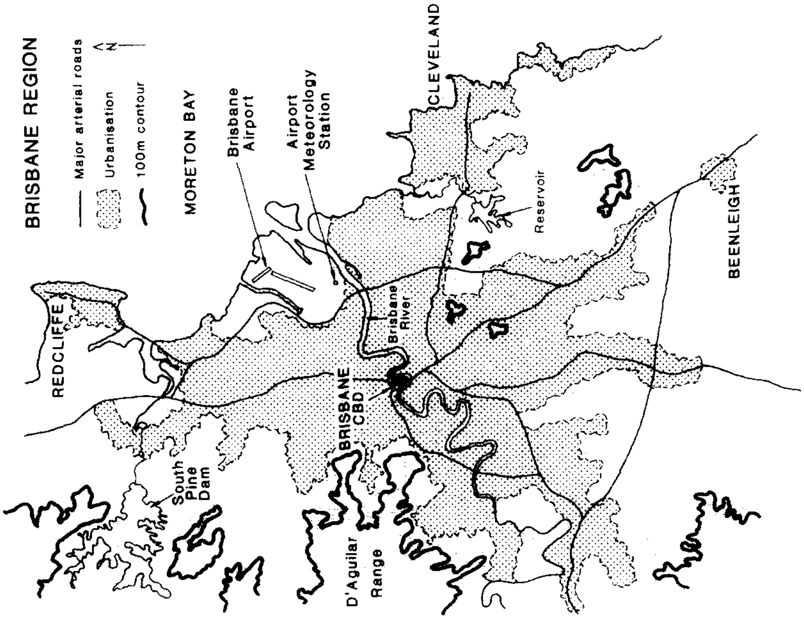

Figure 1. Regional locality plan

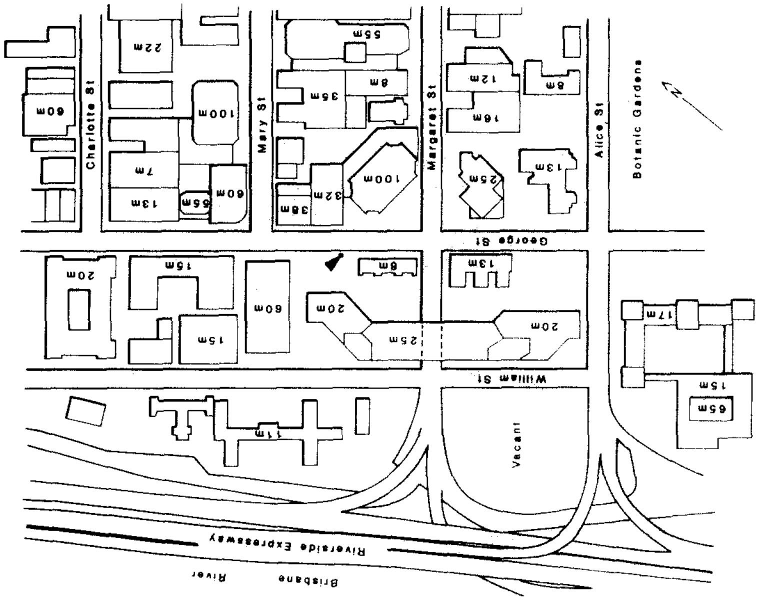

Figure 2. Inner city environs of anemometer station (▲)

The Brisbane Airport Meteorology Station located some 10km from the CBD is used as a reference. Observations of the 10-minute mean wind speeds at 10m height have been made since 1950 and the Brisbane wind climate is established from analysis of these records.

4.2. Instrumentation

The station consists of a FWS100 lightweight 3 cup anemometer and wind vane linked to a data logger and modem. A 10W solar panel trickle charges the battery power supply. The anemometer and wind vane are positioned 1m apart atop a 3m mast. Robust equipment was selected for fear of vandalism. The station was positioned adjacent to a telecommunications manhole to facilitate connection to the telephone network and provide protection for the data logger and modem.

The data logger is based on the Motorola MC146805E2P microprocessor chip and was programmed [14] to detect pulses from the anemometer and wind vane at 30Hz and produce an average value for a 3-second period. The mean wind speed and direction for every 10-minute period of the day as well as the maximum wind speed (averaged over 3 seconds) and its direction during that period are recorded. Data is downloaded from the station every three days and stored for later analysis.

Static calibration of the anemometer revealed good linearity with a starting velocity of less than 0.5m/s. A first order analysis of the dynamic response of the anemometer gave a distance constant of approximately 3m. The wind vane has a direction resolution of 7.5°. Periodic cleaning and recalibration of the instrumentation is undertaken to ensure reliability of results.

5. WIND TUNNEL TESTS

A 1:200 scale model of the inner city region within a 300m radius of the station was available and although a somewhat larger scale than ideal, because of blockage effects (approx. 12%), wind tunnel tests were undertaken. The 2m by 3m by 14m long recirculating BLWT in the Department of Civil Engineering was used in this study. A suitable suburban boundary layer simulation ($z_0 = 0.2$m) at a scale of 1:200 was formed using a fence and cup/block roughness elements. The mean velocity and turbulence intensity profiles are shown in Figure 3. The spectrum of the longitudinal component of velocity was in good agreement with the Deaves and Harris model [12] at this scale. The velocity scale was approximately 1:2 making the time scale 1:100.

A DISA hot wire was mounted vertically at 15mm at the station position and was sampled at 100Hz for 36 seconds using a PC based data acquisition system. The signal was low pass filtered at 16Hz. The observation time corresponds to 1 hour and the cutoff frequency corresponds to a full scale averaging time of 3 seconds - that of the full scale instrument. Mean, peak and standard deviation of wind speed were obtained. It is recognized that in such highly turbulent flows, mean speeds are likely to be overestimated and turbulence intensity underestimated when using single hot wire anemometers which are direction insensitive.

At the beginning and end of each run the hot wire was positioned at the reference position, located away from the influence of the model. Later, with the model removed, this reference velocity was related to the velocity at a height of 1m above the turntable centre. The velocity at this position was used to obtain velocity ratios (V_{city}/V_{1m}) for every 15° wind azimuth. Drift corrections were made from these two 'calibration' measurements and were typically less than 5%. The velocity ratios presented here are the average of four runs.

In a separate test, wind direction information was obtained by monitoring a tuft of wool located at the station position. The variation of wind direction was significant; typically +/-30° and this remains a difficult task at model scale.

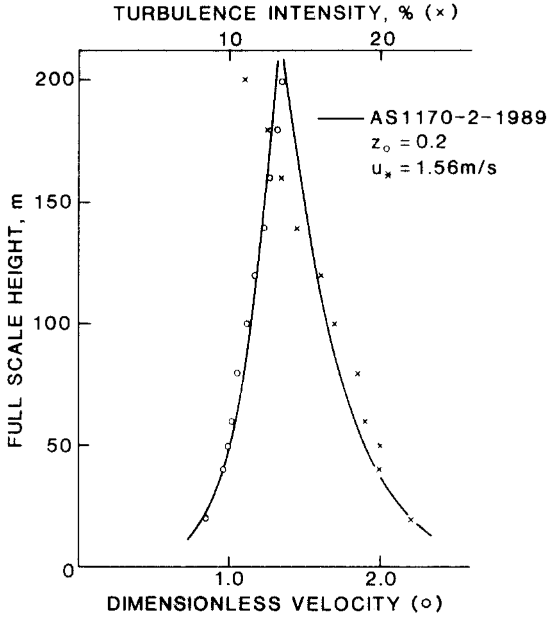

Figure 3. Mean velocity and turbulence intensity profiles

6. RESULTS

6.1. Analysis of full scale measurements

The mean(10 min) and gust(3 sec) wind speeds obtained during daylight hours (7am to 7pm) for each season have been analysed to produce directional probability distributions. Where there is a significant number of observations, both mean and gust speeds are reasonably well fitted to Weibull distributions (equation(1)). Figures 4 and 5 show the observed and predicted all direction probability distribution for mean and gust speeds for winter 1990 respectively.

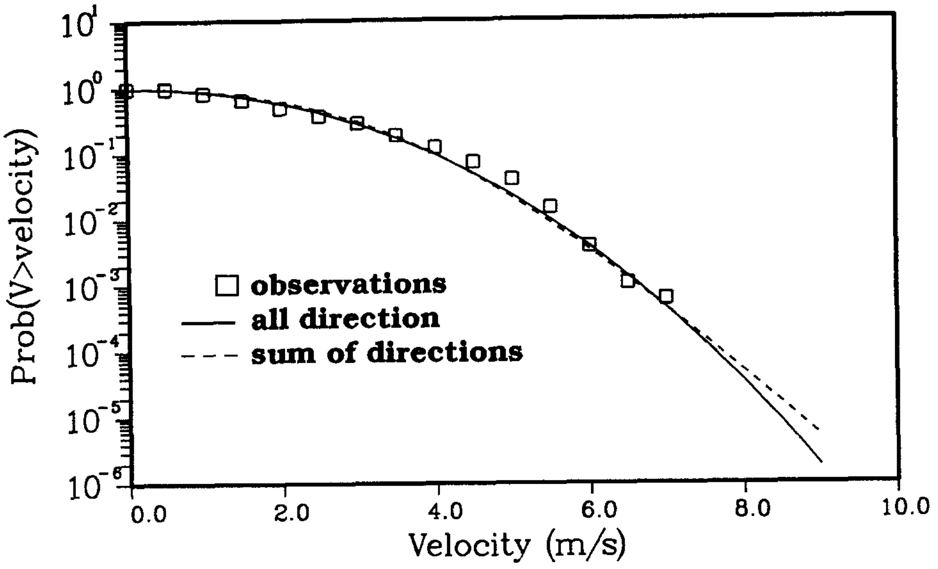

Figure 4. All-direction probability distribution for Winter 1990 mean speeds

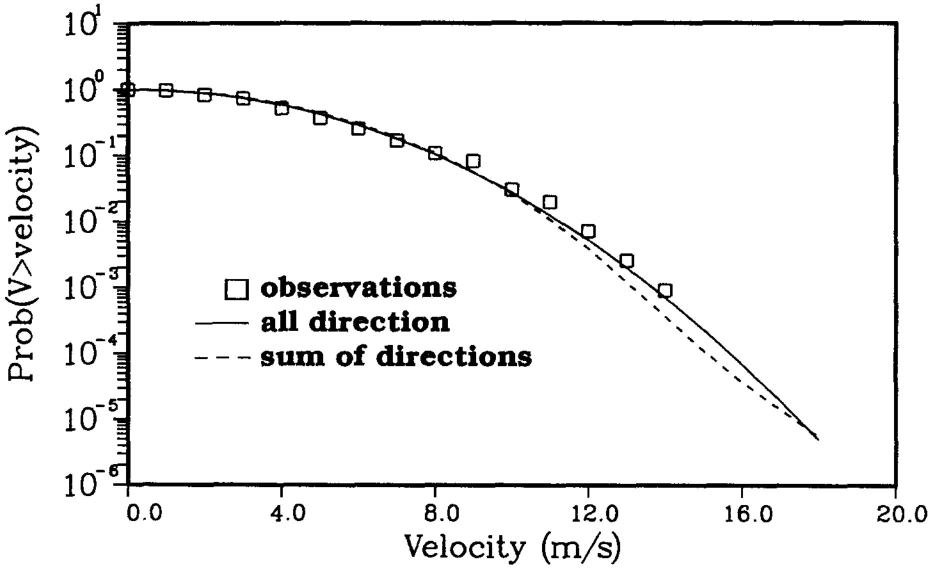

Figure 5. All-direction probability distribution for Winter 1990 gust speeds

Also shown in each figure is the distribution formed by summing the fitted Weibull distributions of the 16 individual directions.

The predicted seasonal velocities of exceedance for June, July and August (winter) 1990 are shown in Figure 6. For directions 0° and 330° there were insufficient mean speed data to fit distributions. Strongest gusts are observed to be along the street (315°). Analysis to date extends to February 1991. Gust/mean speed ratios for all months analysed to date indicate a ratio of approximately 2 for mean speeds greater than 5m/s.

6.2. Correlation of city and airport mean wind speeds

The Brisbane Airport Meteorology Station records 10-minute mean wind speeds from the 10m SYNCROTAC 3 cup anemometer every half hour. The ratio of city mean to corresponding airport mean speed, as well as city direction, has been correlated with wind direction at the airport. Figures 7 and 8 present the results obtained for measurements taken between May 1990 and January 1991. Two full scale data sets are presented based on a conditional minimum airport mean speed of 0 and 5 m/s respectively.

Also shown in Figures 7 and 8 are the predicted city/airport speed ratios and city wind direction obtained from the wind tunnel test. The city/airport ratios have been obtained according to equation (2).

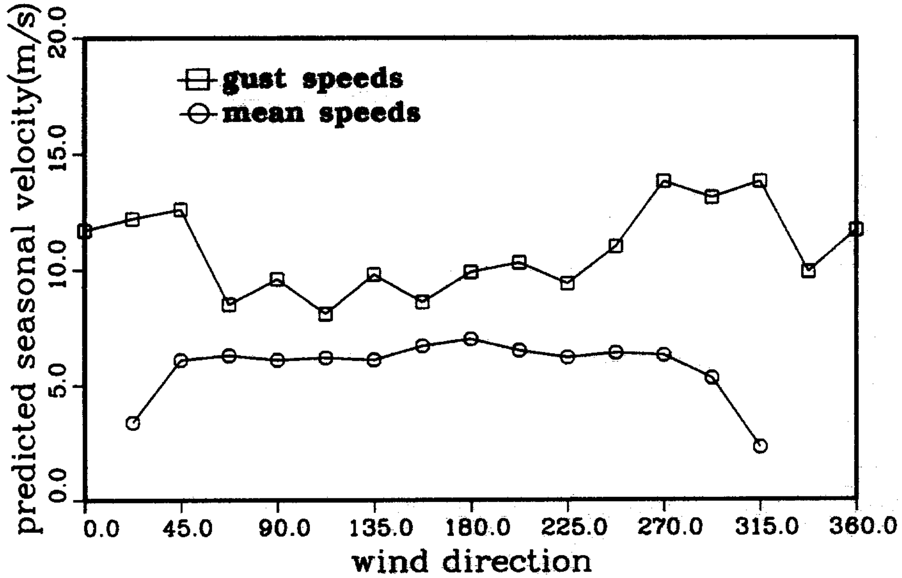

Figure 6. Predicted seasonal exceedance velocities for Winter 1990 speeds

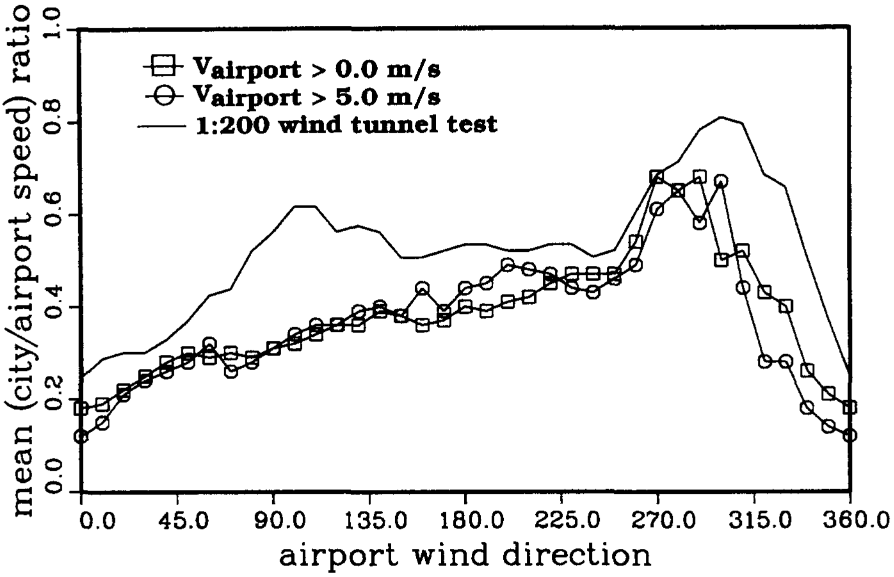

Figure 7. Variation of wind speed ratio with direction

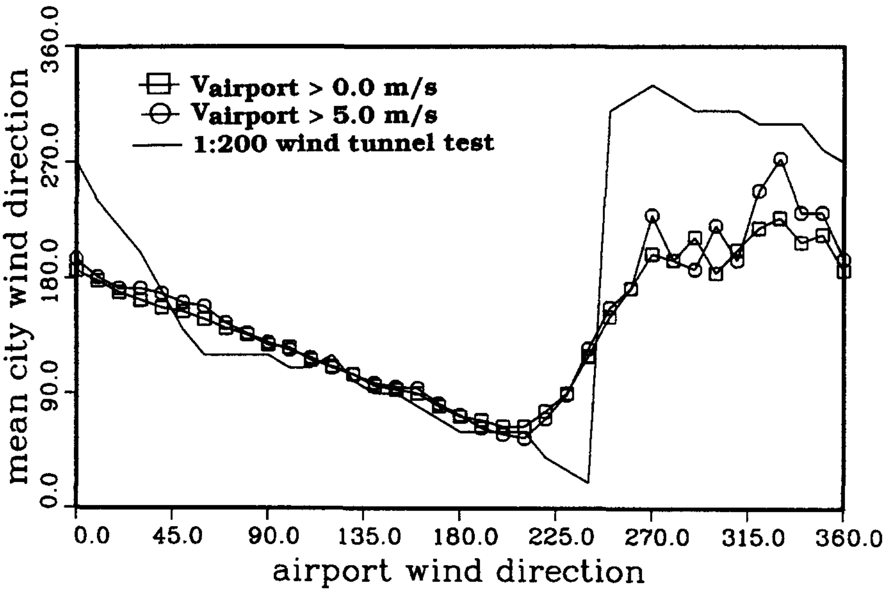

Figure 8. Regression curve for wind direction

$$V_{city}/V_{airport} = V_{city}/V_{200m} * V_{200m}/V_{airport} \qquad (2)$$

where V_{city}/V_{200m} is equivalent to the ratio measured in the wind tunnel and $V_{200m}/V_{airport}$ is obtained from [12] as a terrain/height multiplier, in this case taking the value 1.37 based on the airport as 10m with $z_o = 0.02$m and V_{200m} being in a suburban terrain with $z_o = 0.2$m.

The general shape of the full scale results are in evidence in the wind tunnel results for both speed ratios and city wind direction. In particular the highest speed ratios occur for westerly winds, although the model deviates significantly as far as measured city wind direction is concerned for these winds. The shortcomings of the model, relatively high blockage, insufficient detailed modelling of the inner city upstream, as well as overprediction of mean wind tunnel speeds and the difficulties in determining model scale wind direction, could explain these discrepancies. Of course only a relatively short length of full scale results have so far been obtained.

The influence of the 100m tall building across the street from the station (Figure 2) can be seen in the general shape of Figure 8. For airport wind directions from 90° through to 210° downwash from this relatively exposed building causes the city wind direction to go from roughly parallel to almost reversed. For other airport wind directions the disturbed wake of the upstream inner city prevents clear identification of flow mechanisms.

7. CONCLUSIONS AND FUTURE WORK

Continuous full scale wind speed measurements on an inner city footpath are being undertaken in order to evaluate wind tunnel methods of predicting the street level wind environment. Initial results have been analysed and comparisons with results from a 1:200 scale wind tunnel test show encouraging agreements. Deficiencies in modelling and small length of full scale observations are believed responsible for discrepancies. A 1:400 scale model is currently under construction and comparisons with further full scale observations will be reported in due course.

Analysis of the anemometer records is an ongoing task as is correlation with the reference wind speed records at the Brisbane Airport Meteorology Station. The project is expected to run for a minimum of three years and should then provide a good data base of full scale measurements.

A second anemometer station has been installed at another problem site in the vicinity of several outdoor eating and shopping areas. It is hoped that the current acceptance criteria for these activities will also be examined with the data from this anemometer station.

8. ACKNOWLEDGEMENTS

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Illidge of the Department of Civil Engineering for their assistance in installing the station.

9. REFERENCES

1 A.D. Penwarden and A.F.E. Wise, Wind Environment Around Buildings, Building Research Establishment Report, Watford UK, 1975.

2 R.M. Aynsley, W.H. Melbourne and B.J. Vickery, Architectural Aerodynamics, Applied Science, London, 1977.

3 N. Isyumov and A.G. Davenport, Comparison of Full Scale and Wind Tunnel Speed Measurements in the Commerce Court Plaza, J. Wind Engng. and Ind. Aero. 1, pp201-212, 1975/76.

4 B.E. Lee and M. Hussain, The Ground Level Wind Environment Around the Sheffield University Arts Tower, J. Wind Engng. and Ind. Aero. 4, pp333-342, 1979.

5 R.C.F. Dye, Comparison of Full Scale and Wind Tunnel Model Measurements of Ground Winds Around a Tower Building, J. Wind Engng. and Ind. Aero. 6, pp311-326, 1980.

6 S. Murakami, K. Uehara and H. Komine, Amplification of Wind Speed at Ground Level Due to the Construction of High Rise Building in Urban Area, J. Wind Engng. and Ind. Aero. 4, pp343-370, 1979.

7 S.Sanada, Y. Iwasa and M.Yoshida, Full Scale Measurement of Environmental Wind in the Shinjuku New Metropolitian Center, J. Wind Engng. and Ind. Aero. 6, pp291-310, 1980.

8 M.Ohba, N. Kobayashi and S. Murakami, Study on the Assessment of Environmental Wind Conditions at Ground Level in a Built-up Area, J. Wind Engng. and Ind. Aero. 28, pp129-138, 1988.

9 S. Kawamura, E. Kimoto, T. Fukushima and Y. Taniike, Environmental Wind Characteristics Around the Base of a Tall Building - A Comparison Between Model Test and Full Scale Experiment, J. Wind Engng. and Ind. Aero. 28, pp149-158, 1988.

10 R.H. Grant, G.M. Heisler and L.P. Herrington, Full-Scale Comparison of a Wind Tunnel Simulation of Windy Locations in an Urban Area, J. Wind Engng. and Ind. Aero. 31, pp335-341, 1988.

11 L.W. Apperly and B.J. Vickery, The Prediction and Evaluation of the Ground Level Wind Environment, pp175-182, 5th Aust. Fluid Mech. Conf., Christchurch, NZ, 1974.

12 D.M.Deaves and R.I. Harris, A Mathematical Model of the Structure of Strong Winds, CIRIA (UK) Report 76, 1978.

13 W.H. Melbourne, Criteria for Environmental Wind Conditions, J. Wind Engng. and Ind. Aero. 3, pp241-249, 1978.

14 Environdata Australia Pty. Ltd., Easidata Mark III Handbook, Environdata, Warwick, Australia, 1989.

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Full-Scale Wind Engineering Measurements in New Zealand

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The aim of the research described in this paper is to measure the wind to better understand it, so that it can be modelled correctly in predictions, and to learn how the wind excites tall buildings. The paper describes two research projects of full-scale wind engineering measurements. One research project captured wind speeds from tower-mounted anemometers in complex terrain which have beencompared with predictions from CFD, wind tunnel measurements and the Australian/New Zealand Standard. The other research project measured the motion of four different tall buildings in Wellington and Auckland and compared those motions with predictions from wind tunnel measurements and the Standard. The research found that the wind tunnel modelling and CFD code Gerris gave results which agreed well with the observations, but that the AS/NZS1170.2 wind speed-up predictions differed significantly when carried out by different organisations. It was found that the building motion could be predicted reasonably accurately using a simple predictive equation based on building properties and the one-year return period design gust wind speed from AS/NZS1170.2.

Keywords**:** Belmont Hill, wind speed-up, complex terrain, topographic effects, field wind speed monitoring, CFD wind modelling, AS/NZS 1170.2, wind tunnel, full-scale wind measurements, tall building motion, human comfort, building accelerations.

Introduction

The paper is primarily focused on two comprehensive full-scale sets of wind engineering measurements, but a brief summary of some historical wind engineeringmeasurements is provided herewith to put the material into context.

The sudden increase in oil prices in the 1970smade NZ realise how dependent it was on imported oil for energy, and so it established an organisation called the NZ Energy Research and Development Committeeto study ways of mitigating this dependency. It also established and partially funded the Wind Energy Task Force which coordinated a cross-disciplinary team of engineers and physicists drawn from universities and government departments. This organisation then carried out a wind energy resource survey beginning in 1974 [Cherry (1980), Edwards, (1990)], which may have been one of the first full-scale wind engineering activities in NZ. Around the same time research in wind energy became more active at the Universities of Auckland, Canterbury and Otago in NZ. For example at the University of Canterbury research on the wind became a major theme, and a boundary layer wind tunnel was built and used to study wind protection by fences [Raine and Stevenson (1977)]. In addition funding was obtained and used to build masts, propeller anemometry and field data acquisition equipment for measuring full-scale wind structure over rural terrain [Flay *et al.* (1982)], over hills and escarpments [Bowen and Lindley, (1974, 1977)], channelling in valleys [Meroney *et al.*, (1979)], and over saddles [Neal (1982)]. At the same time research on wind pressures on buildings was being carried out at the University of Auckland [Feasey and Freeston (1977)]. Full-scale measurements of wind structure were carried out by Jackson at the Ministry of Works Central Laboratories using an instrumented tower in Wellington [Jackson, (1976)]. Since that very active time of wind engineering research in the 1970s, motivated to a large degree by interest in wind energy, there has been much less full-scale wind engineering measurements in more recent

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times in NZ.Protection of kiwi-fruit motivated work on wind protection by fences [Richards (1986)], and validation of wind tunnel predictions of pedestrian level winds around proposed buildings motivated some further full-scale work [Carpenter (1990), Chiappini and Flay (2004)] but there was much less interest in wind measurements than in the previous decade. NIWA records wind data from multiple sites around NZ mainly for weather forecasting, which are also analysed to obtain reference wind speeds for wind loading [e.g. Reid (1987)], and that activity has beenon-going. However, since the 1990s there has again been renewed interest in wind energy, and considerable efforts have been undertaken to conduct wind speed measurements for assessing the wind resource of potential NZ wind farm sites. However, in general these data are not published.

The full-scale measurements of wind speed-up over hills, and of tall building motion that are the main focus of the present paper were motivated by shortcomings in prediction methods that had been observed by the authors.

Part 1: Wind Speed-up Measurements Over Belmont Hill

New Zealand's hilly, often mountainous, terrain is oriented approximately SSW-NNE creating a barrier 1500 to 2000 m high along both its main islands and is in the path of often strong, predominantly westerly winds that occur at these latitudes. The wind flow is significantly modified by the hilly terrain over which it passes. These topographic effects on wind speed are recognised in the Australia/New Zealand Loadings Standard, AS/NZS 1170.2 (2011) – a reference document for the New Zealand building code.

Within the Standard wind forces are prescribed as the product of a referencegust dynamic pressure of the wind and a shape-related pressure coefficient, C_{pe}. Topographic enhancement is allowed for with a topographic multiplier, M_t, which is made up of a hill-shape multiplier ($1<M_h<1.71$ resulting in up to 3x wind force), which depends on hill shape and steepness and the distance of the site from the hill crest, and a Lee Multiplier, M_{lee} to be applied within Lee Zones downwind of hill ridge lines. While the physical basis for including these effects is clear, the methods to predict these factors are very simplified and need improvement. This fact combined with some recent severe wind events: the 2004 Molesworth Windstorm (Reid and Turner, 2004); the 2007 Taranaki Tornadoes (Reese *et al.*, 2007); the 2008 Greymouth windstorm (Revell *et al.*, 2009); and several other recent storm events, have caused renewed interest in wind engineering and a questioning of the guidance offered by the loadings standard. Consequently the present research project was set up to provide the basis for reviewing the calculation methods in the Standard for the topographic multiplier M_h.

This paper presents some of the results from an experiment to compare measured wind speedups over the rugged Belmont Regional Park in the Wellington area of New Zealand with wind speedups estimated from the AS/NZS 1170.2 loadings code, through computer modelling, and through wind-tunnel modelling. The computer modelling was done with the CFD code Gerris, developed in-house by NIWA, and with WASP. For a detailed description of Gerris, see Popinet (2003), and Popinet *et al.* (2004). Further details on the research are available in the final report on the research project, King *et al.* (2012), and aspects of the research have been presented in conference papers (Flay *et al.*, 2011, Flay *et al.*, 2012, Flay *et al.*, 2013).

Measurements of Wind Speed-up

The research project was focused on measurements and modelling of topographic speed-up effects within the Belmont Regional Park near Wellington. The area is typical of much New Zealand hill country (see Fig. 1) where important infrastructure is located. The terrain is not simple - a lower ridge upstream (for northwesterly winds) and approximately parallel to the highest elevations adds complexity to the terrain. Furthermore the valley behind this ridge could be expected to be somewhat sheltered. Vegetation was mainly short to moderate grass with the

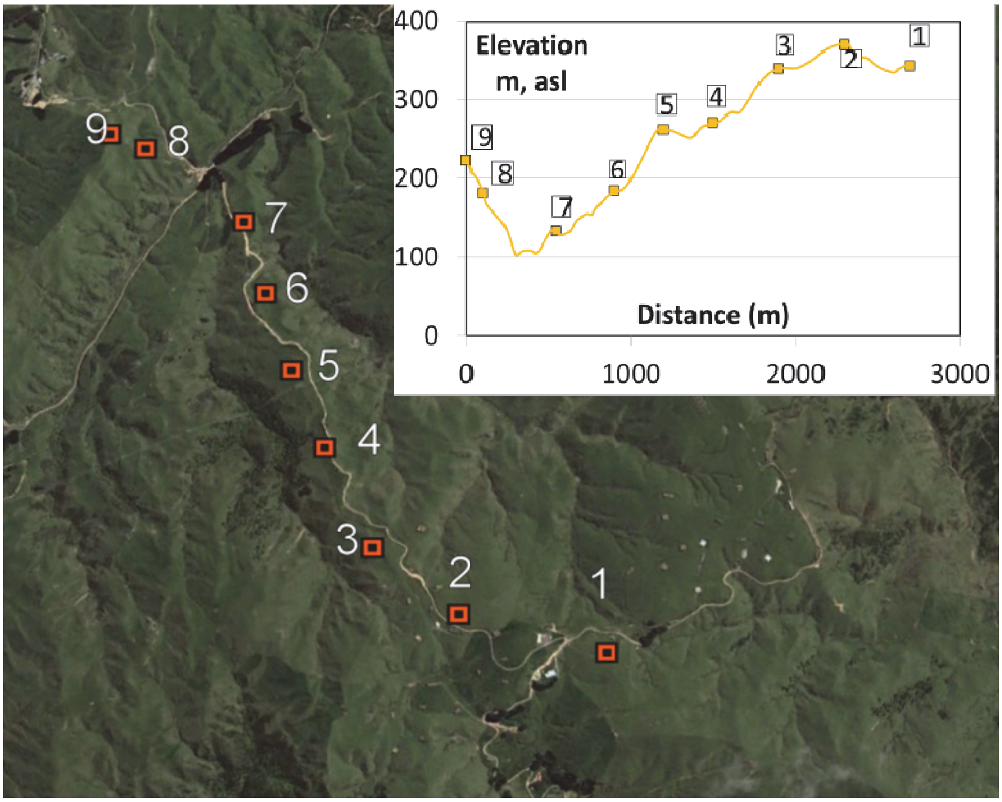


Fig. 1. An image looking down on the typical New Zealand hill-country of Belmont Regional Park near Wellington, showing locations and profile of heights for the instrumented masts.

few trees and scrub in the vicinity, confined to gullies, giving a design wind terrain roughness classification of 2 (according to AS/NZS 1170.2), although the terrain perturbations (ridges and valleys) are much larger than the terrain roughness.

Nine portable masts (5 m high) with Vector A101m 3-cup wind speed sensors (accurate to 1% in the 10–55 m/s range) and Vector W200P wind vanes (direction accurate to ± 3°) were deployed. Siting of the masts was aided to some extent by prior CFD modelling with the CFD code Gerris under idealised NNW flow but the main consideration was reasonable access to the masts from roads/tracks in the park.

Topographic information describing this site was used to create a digital terrain model for the CFD (Gerris and WASP) investigations by NIWA and a physical model at a scale of 1:2000 for the wind tunnel investigation carried out by Opus. Wind speedups along the ridge shown in Fig. 1 were also determined using the codified procedures in AS/NZS 1170.2.

Full-scale Observations of Wind Speedup

Several sets of full-scale measurements of wind speed were made over the first 6 months of 2011. The paper focuses on the 18-hour observation period from 12 noon on 6 February, to 6 am on 7 February 2011 when the wind direction was approximately 345°. Fig. 2 shows the site looking upwind for this direction. Three-second wind observations were collected at all 9 masts during this period. Means, maxima, standard deviations, turbulence intensities plus directions of average and maximum winds for this period are displayed in Fig. 3 which shows that the wind direction is nearly constant across the nine masts from about 345° except at the sheltered

Fig. 2. View from the southeast showing the area studied, looking directly upwind for the 345° wind direction. Porirua can be seen in the background. Ridge used for Met masts and anemometers is slightly to right of centre.

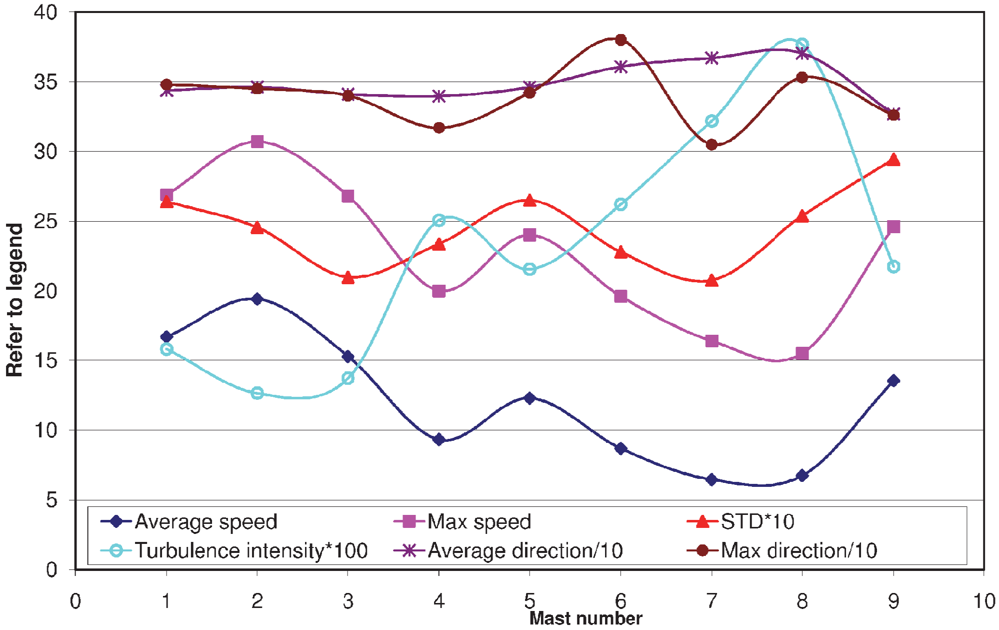


Fig. 3. Belmont Hill full-scale wind statistics for 6 - 7 February 2011 from the 5-m anemometers. (Average speed (m/s), Max speed (m/s), STD*10 (m/s), Turbulence intensity*100 (%), Average direction/10 (degrees), and direction of Max speed/10 (degrees)).

Table 1. Observed mean and gust speedup multipliers for a wind direction of 345° for the nine mast locations

Mast	1	2	3	4	5	6	7	8	9
Mean	1.56	1.82	1.44	0.87	1.15	0.82	0.60	0.64	1.27
Gust	1.46	1.66	1.35	1.05	1.25	1.00	0.84	0.81	1.31

masts 6, 7 and 8; The average speeds and the maximum gusts vary very similarly across the masts; The standard deviation (STD) of the wind speed is fairly constant at about 2.5 m/s across all the masts; The maximum gust at each mast is predicted within a few % by the mean speed plus 3.7*STD.

In order to determine speed-ups based on these observations, an estimate of the wind speed at a 5 m elevation at a neighbouring site at a location not affected by the Belmont Hills was required. Wellington Airport wind records (Carpenter and Reid, 1990) were used for this purpose as hourly means and maximum wind gusts data are available there at a height of 7 m, and so were adjusted to a height of 5 m and by a1.1 channelling factor for the site, for each of the 18 one-hour periods for which the Belmont observations were available. The averaged results of these calculations for both mean and maximum gust speedups are shown for each mast location in Table 1. Note that these are ratios of mean/mean and gust/gust which is why the gust speedups are lower than the mean speedups in some cases. Mast 2 is the most elevated and has the highest speed up, whereas Masts 4, 6, 7 and 8 are sheltered behind ridges and have the lowest speedups, generally less than 1.0.

AS/NZS 1170.2 Loadings Standard Estimates of Wind Speedup

The Wind Loading Standard (AS/NZS 1170.2, 2011) has provision for determining the effect of hills on the wind speed. It is a simplified approach, based on various published data from a number of wind tunnel tests and full-scale measurements. When one attempts to apply this procedure to the Belmont Hill that was used for the full-scale experiments, it is immediately apparent that the procedure is very difficult to apply. The procedure is based on two-dimensional hills, whereas the instrumented Belmont Hill is very three-dimensional. Furthermore, the full-scale measurements are along a ridge as shown in Figs. 1 and 2.

The approach in the standard requires the user to look upwind over an arc of +/- 22.5° with respect to the direction under consideration, and to determine the worst case for the topographic multiplier. This means that one needs multiple contours through each point of interest in order to determine the hill-shape multiplier, M_h.

The equation for the hill-shape multiplier (AS/NZS 1170.2, 2011) is:

$$M_h = 1 + \left(\frac{H}{3.5(z + L_1)} \right) \left(1 - \frac{|x|}{L_2} \right) \tag{1}$$

where$x$ is distance from the crest, z is height, H is hill height and L_1, L_2 are scaling lengths based on the hill height and the hill slope.

Calculations for the gust hill-shape multipliers were carried out for each of the mast locations using AS/NZS 1170.2, (2011) for the 345° wind direction by NIWA. This involved using software that had been developed by NIWA to implement the speedup method of the standard. The approach did not appear to follow that in the standard exactly and in the case of the presentlarge complicated hill, the method did not determine a flat “upwind” location as the beginning of the hill, but calculated the speedup from bumps or hills on the larger scale hilly terrain. The estimates from NIWA are given in Fig. 4, and because they were very sheltered, AS/NZS 1170.2 estimates were not performed for mast locations 6 and 7 by NIWA.

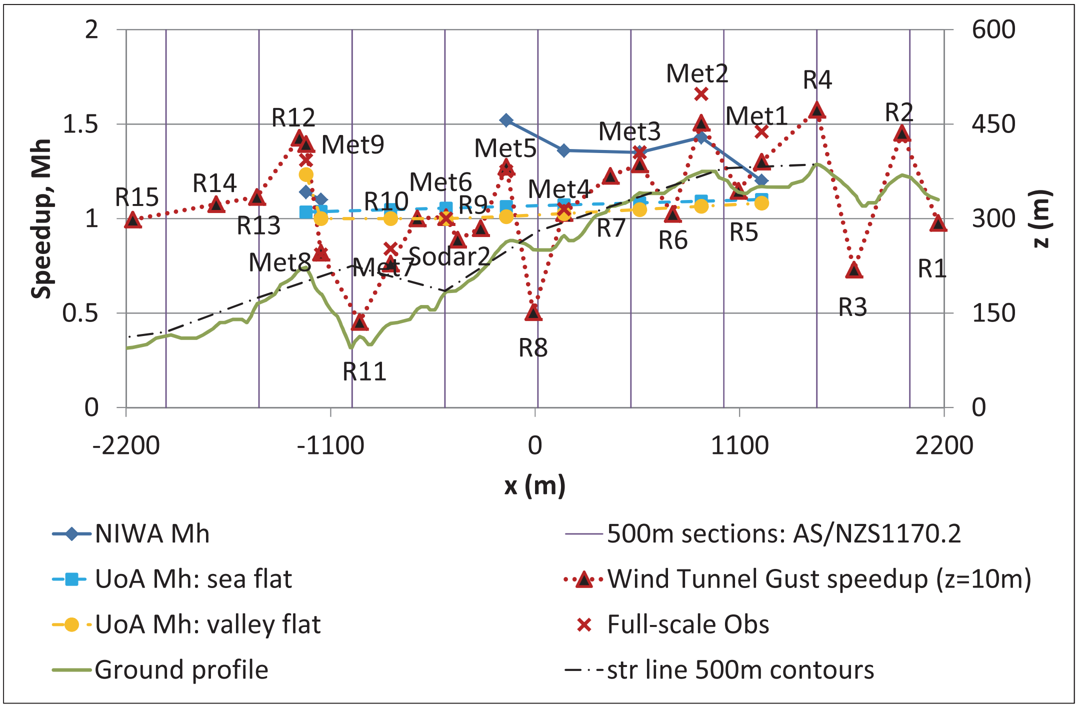


Fig. 4. Ground contour along the measurement line, 500 m segments upwind from the crest. Gust speedups from full-scale observations, the wind tunnel, and NIWA and UoA using AS/NZS1170.2. Two sets of UoA results are shown. The "sea flat" estimates assume that the "hill" starts at sea level and the "valley flat" estimates assume that the valley at -500 to -1000 m is flat, and that the hill for masts Met 1 to Met 5 starts at an elevation of 225 m. Wind is blowing from left to right.

Independent estimates of the speedup were also made by the University of Auckland (UoA) using the procedures outlined in the standard and its commentary, except that only the 345° wind direction was analysed, not the worst contour in upwind 45° arcs, as specified in the standard. Difficulties in dealing with the valley shown at top-left of Fig. 1, and near the top of Fig. 2 resulted in the UoA carrying out two sets of predictions of wind speed-up. One set (sea flat) assumed that the "hill" started at the flat sea, and the other set (valley flat) assumed that the large valley between masts 6 and 9 could be assumed to be flat, thus resulting in the "start" of the hill at this location for masts further downwind. For the latter calculations, the speedup at masts 6, 7 and 8 are really undefined, since they are in the valley, and thus one would expect these masts to be relatively sheltered from wind at 345°. Mast 9 upwind of the valley was assumed to be on the crest of a hill starting at the sea. The speedup predictions from the standard for the gust speed are shown in Fig. 4. It is clearly evident in Fig. 4 that the estimates using AS/NZS1170.2 from NIWA and UoA are very different. This means that the Standard is very open to error in its use in such complex terrain, which is very common in New Zealand.

This finding is some cause for concern, and may mean that this section in the Standard on the hill-shape multiplier should be subjected to a rewrite in the future to reduce possible ambiguity and error in order to reduce the potential hazard of wind and the risk to important built infrastructure (Reid and Turner, 2004, Reese *et al.*, 2007, Revell *et al.*, 2009, Carpenter and Reid, 1990).

WASP estimates of Wind Speedup

The potential flow solver WASP, developed by the Wind Energy Division at the Technical University of Denmark was used to predict speedup. It is a widely used wind energy and wind

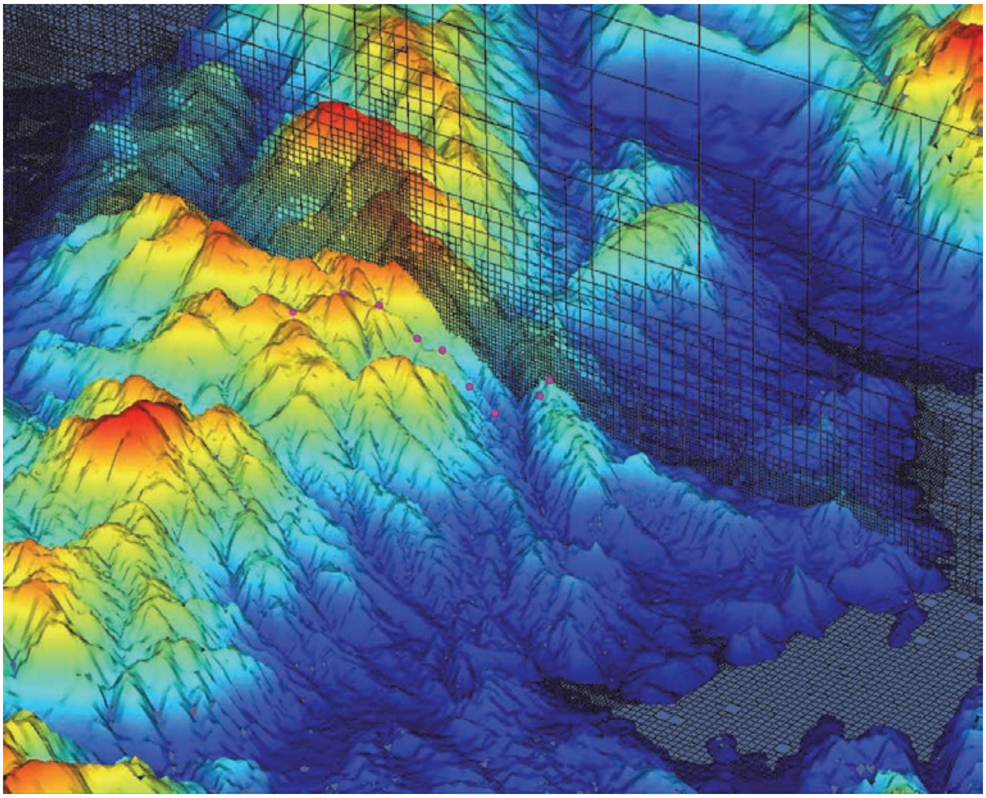


Fig. 5. Gerris topography (highest peak in foreground ~ 400 m), mast locations (purple dots 1 to 9 from left to right) and adaptive grid along a NNW-SSE cross-section through Belmont Park (northern half of the domain) viewed from the NE. The wind flows from right to left in this diagram.

engineering tool. WASP is described in Troen and Petersen (1989) and is similar to models based on the analysis of Jackson and Hunt (1975). WASP solves, for a particular location, the potential flow perturbation by the terrain for a unit wind vector in the undisturbed wind direction. The potential flow solution is then modified to account of upwind and local surface friction. For the WASP calculations undertaken here, terrain data were from a 20 m contour DEM (so slightly coarser than that used for the Gerris and wind tunnel models) and terrain with characteristics of Terrain Category 2 (AS/NZS 1170.2, 2011) with a roughness length z_0 = 0.02 m was assumed. Calculations were done at 40 m intervals on a grid (rotated 15° west of north) covering the Belmont study site for an altitude of 5 m. Hill-shape multipliers for the mast locations ranged between 0.74 at Mast 7 and 1.72 at Masts 2 and 9, although some other locations (not at mast positions) had higher values.

Gerris Estimates of Wind Speedup

CFD modelling was also done using the code Gerris, which uses a time varying, adaptive grid to solve the Navier Stokes equations, as described in Popinet (2003). The topography was based on high resolution terrain contours every 5 m in the vertical direction and the Gerris model resolution is 10 m in the vertical and 40 m in the horizontal direction at the highest resolution. The model was run for 20 minutes of simulated time to allow the flow to settle down and then statistics (means and standard deviations) were generated over the next 20 minutes at heights of 5 m at each mast location. The inflow condition was a wind from 345° with a logarithmic velocity profile based on a roughness length of 20 mm and a speed of 20 m/s at 500 m –Terrain Category 2

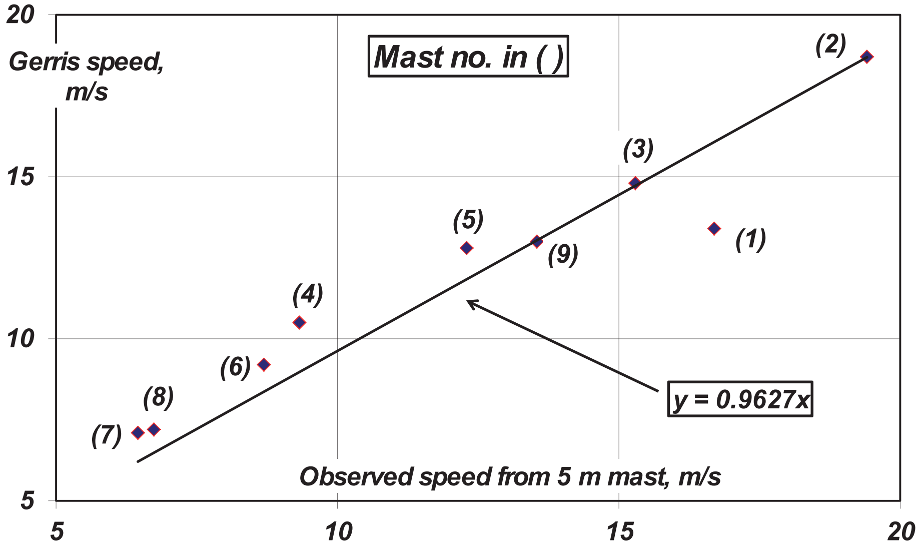


Fig. 6. Observed versus Gerris-modelled mean wind speeds at the selected sites in the Belmont Hills.

(AS/NZS 1170.2, 2011). A free slip lower boundary condition was used and it was assumed that the dominant turbulence production in the lower layers would be created by flow separation off the fairly rough upstream terrain. No parameterisation of sub-grid scale turbulence was added to the model. The Gerris topography, location of masts and computational grids for a horizontal and vertical slice are illustrated in Fig. 5.

Comparison between the observations and the results of the model simulations for this flow can be seen in Fig. 6. Apart from at the easternmost mast 1, there is remarkable agreement between observed and model simulated average speeds at the masts with a correlation of 0.96. The STD of the wind speed is very close to 3.5 m/s across the mast array. This is a little higher than the observed STD of about 2.5 m/s across the masts and is probably explained by the lack of a sub-grid scale turbulence dissipation scheme. At this resolution, it is clear that the Gerris CFD model is representing the mean modification of the incoming flow by the orography very accurately, but is overestimating the turbulence.

However, in order to compare the Gerris results with the other methods, these wind speeds need to be expressed as speed-ups. For the mean speed-ups, this was done by dividing the 5 m wind estimated by Gerris at each mast location by the corresponding 5 m wind at the inflow boundary, namely 11.18 m/s. In order to do the same for the gust-based speedups the gust speed was estimated as the mean speed plus 3.7 times the standard deviation, the same method as used for the wind tunnel calculations in the next section.

Wind Tunnel Measurements of Wind Speedup

The wind tunnel tests were undertaken by Opus and more details are available in a separate report [Carpenter *et al.* (2011)]. A scale of 1:2000 was selected for the wind tunnel model. The choice of scale wasa compromise between competing requirements. In general, a larger model scale is desirable for accuracy in positioning the wind speed measuring equipment, and for the aerodynamic simulation (e.g. Reynolds Number), while a smaller scale is desirable in order to be able to model a sufficiently large area around the test site, and to fit the model into the wind tunnel. The Opus wind tunnel turntable is 2.6 m in diameter, which allowed a full-scale diameter of width of 5.2 km at the chosen scale of 1:2000. It was decided that it was necessary to include at

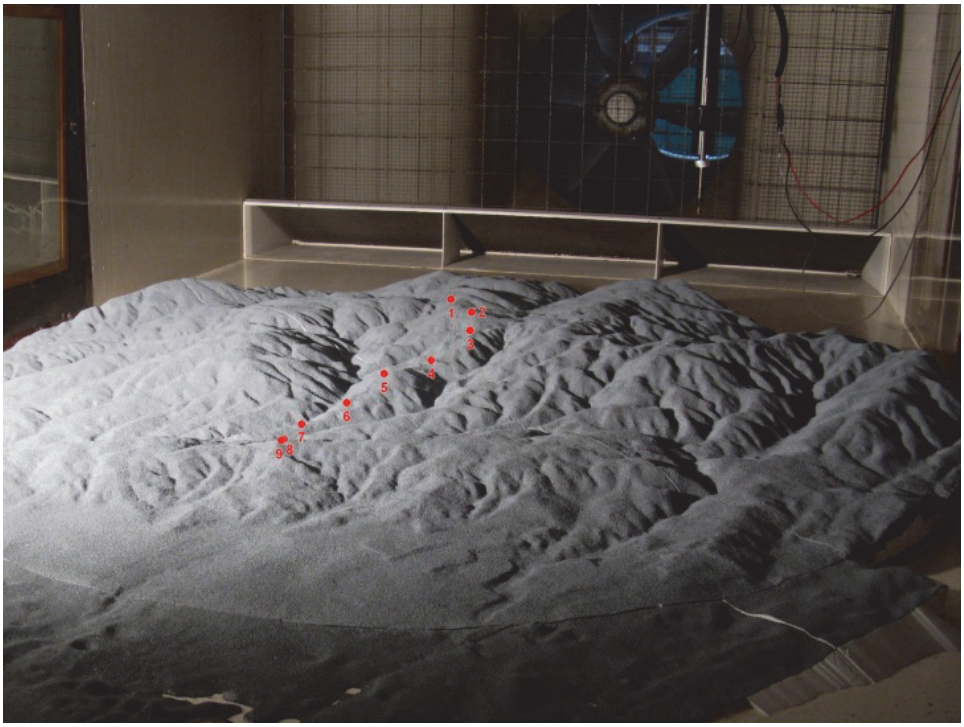


Fig. 7. The hill model in the wind tunnel, seen from the northwest, showing the locations of the nine cup anemometers, Met1 to Met9 (along the central ridge).

least this much area of the Belmont Regional Park study area in order to be able to include an adequate area of model upwind of the measurement sites.

5 m contour data of the study area were obtained from a 2011 aerial survey. The data were supplied by the Greater Wellington Regional Council. The model was made from high density white polystyrene foam using a numerically controlled milling machine.

It was aimed to reproduce a terrain roughness Category 2 boundary layer simulation (z_0 = 0.02 m) the same as used in the CFD WASP and Gerris simulations. After some experimentation, the surface roughness selected for the model consisted of a dense coating of sand glued to the model surface (grade 20–30 standard sand, which has 0.7 mm typical grain size) covered with a single coat of paint. Fig. 7 shows the 1:2000 scale model in the wind tunnel, viewed from the northwest, and shows the locations of the nine cup anemometers.

The height of the NIWA anemometer poles was 5 m, equivalent to 2.5 mm at a scale of 1:2000. This was the lowest height above the surface that was measured in the wind tunnel study. The wind speed measurement probe was therefore very close to the model surface height, with potential influences due to height measurement error or model surface irregularities. It was therefore considered that the measurements at 2.5 mm height had the possibility of being less consistent than measurements at greater heights. For this reason a height of 10 m (5 mm model scale) was selected for a regular grid of speed measurements, over the study area approximately 2.5 km long by 1 km wide. The locations of the wind tunnel measurement stations can be seen in Fig. 8, which also shows the nine cup anemometer locations, Met1 to Met9.

All testing was carried out at a wind tunnel mean speed of 12.0 m/s at a height of 500 mm. The wind speeds were measured using a single-wire hot film anemometer probe with the wire horizontal, in order to measure the wind speeds blowing up and over the hills, but not to measure

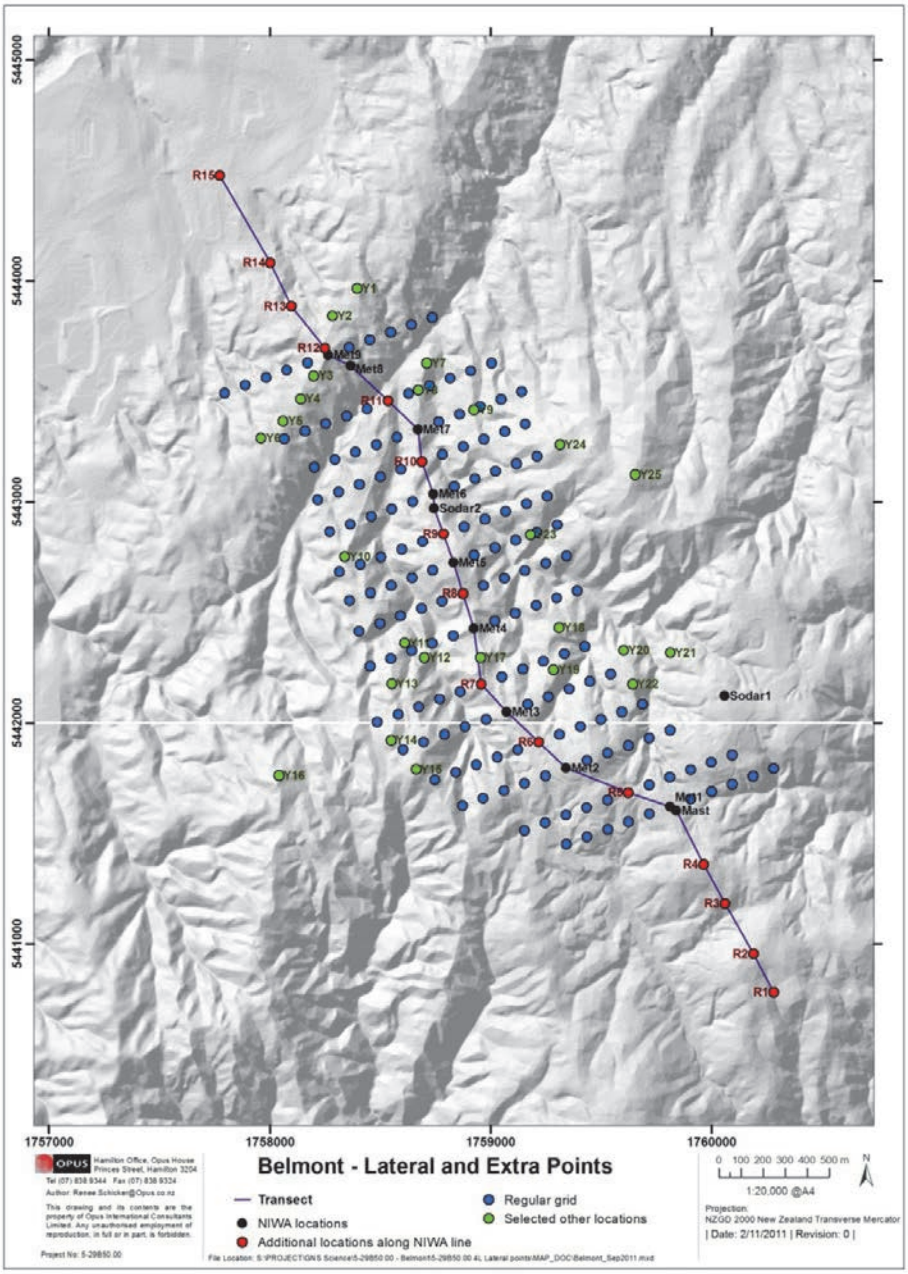


Fig. 8. Plan view of the wind tunnel measurement locations, including cup anemometer locations Met1 to Met9 (along the drawn line).

any wind speed component across the wind tunnel. It was anticipated that the lateral velocity component would be the smallest of the three components.

The wind speeds were recorded at 1000 Hz, typically for 1 minute at each location. Some selected locations, including the locations of the full-scale anemometers and the reference atmospheric boundary layer measurements (to develop the correct onset wind structure) were recorded for 2 minutes. In the subsequent analysis, a 250 Hz moving average filter was applied to the recordings, which was equivalent to applying a 3-second moving average at full scale. This was calculated through equivalence of the reduced velocity *V*/*Lf*, where *V(model)* = 7.4 m/s mean speed at 5 mm height, and *V(full-scale)* = 20 m/s nominal mean speed at 10 m height.

The selected wind tunnel measurement locations included the locations of the nine NIWA 5 m high cup anemometers, as well as 150 locations in a regular grid, measuring approximately 2.5 km long by 1 km wide, and are all shown in Fig. 8.Measurements in most locations were made at model heights equivalent to full-scale heights of 5 m, 10 m, 20 m, 50 m, 100 m, 200 m, 500 m. All measurement locations were tested for wind direction 340°. Some locations were also tested for directions 320° and 360° and linear interpolation was used to calculate the speeds for a wind direction of 345° for comparison with the site wind speed measurements and the other predictions from CFD and the wind loadings standard (see Fig. 4).

The speed measurements at the range of heights mentioned above were used in Matlab to interpolate speeds elsewhere as a function of height. Fig. 9 shows such an interpolation obtained from the measured gust hill shape multipliers for a wind direction of 340°, with the wind shown blowing from the left in the plot. The cross-section shown is drawn through all the NIWA cup anemometer measurement locations which are marked as black dots, plus additional selected locations marked as red dots. It is therefore not a section along a straight plan line. The *x*-axis in the plot is calculated as distances along a 340° bearing, with the model centre as the arbitrary zero. It is clearly evident in Fig. 9 that the highest speedups occur near the tops of peaks, and that the lowest speedups occur in the valleys. This is as-expected.

Fig. 10 shows the mean and gust hill shape multipliers measured in the wind tunnel at a height of 10 m above local ground level for a wind direction of 340°. It is of interest to observe that the mean speedups show the most variability and are both the highest near the hill tops, and the lowest in the valleys, compared to the gust speedups which do not change so much. Fig. 11 shows a colour contour plot of the gust hill shape multipliers measured in the wind tunnel for a wind

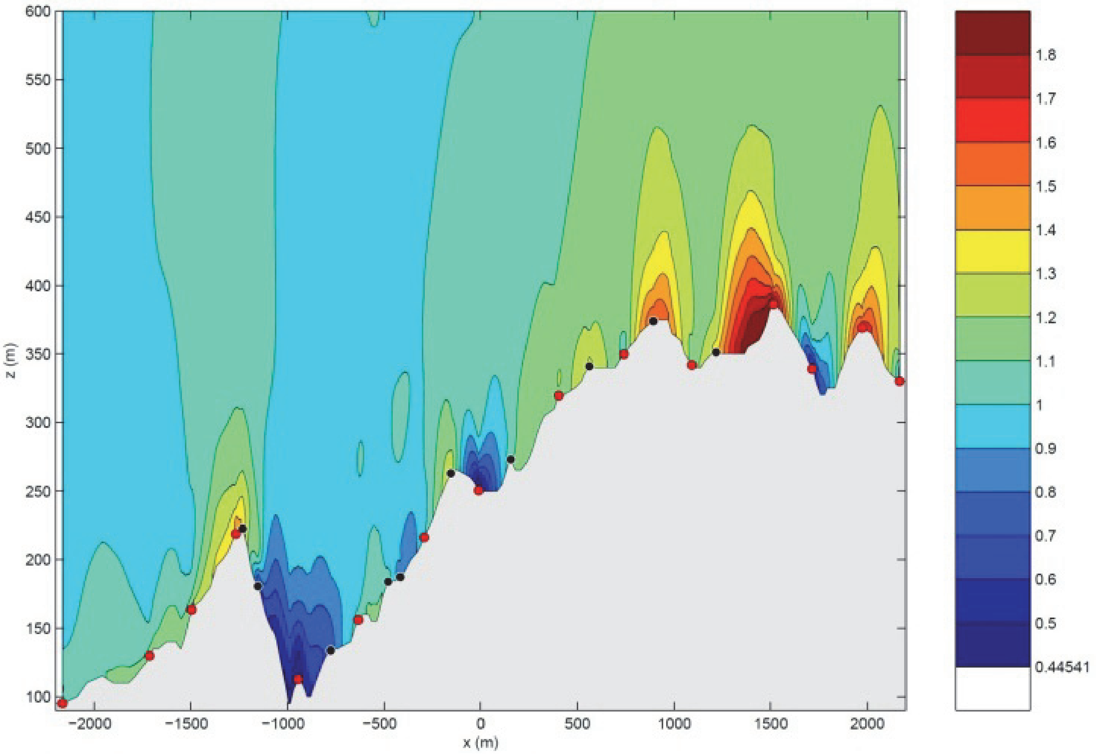


Fig. 9. Cross-section of the gust hill shape multipliers measured in the wind tunnel for a direction of 340°. The wind is blowing from the left.

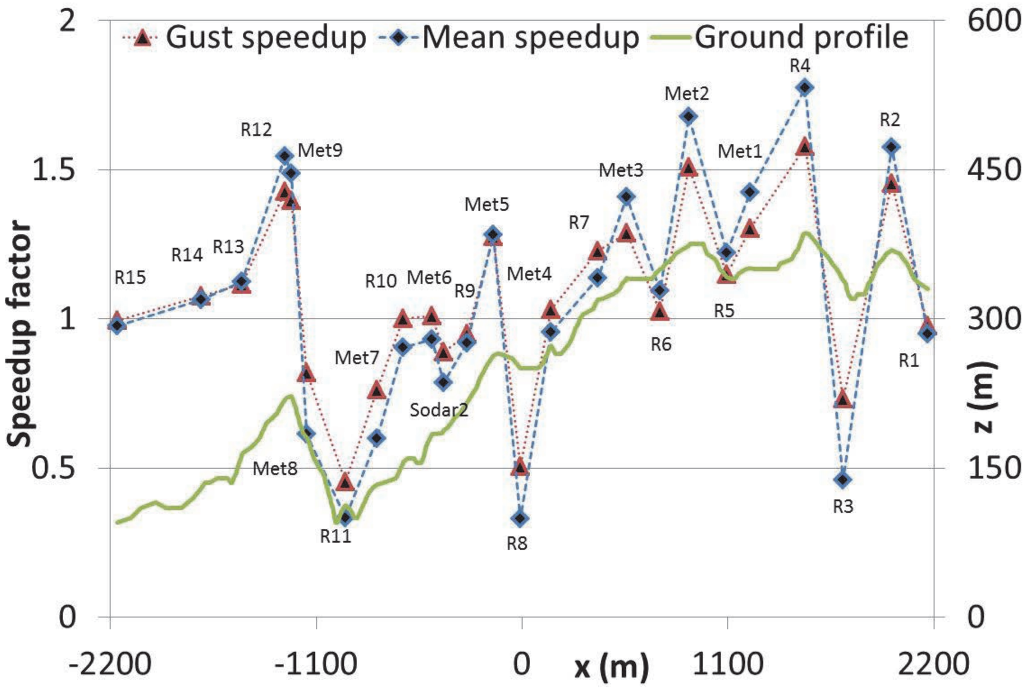


Fig. 10. Wind tunnel mean and gust hill shape multipliers at a height of 10 m above local ground level for a wind direction of 340°. Wind is blowing from left to right.

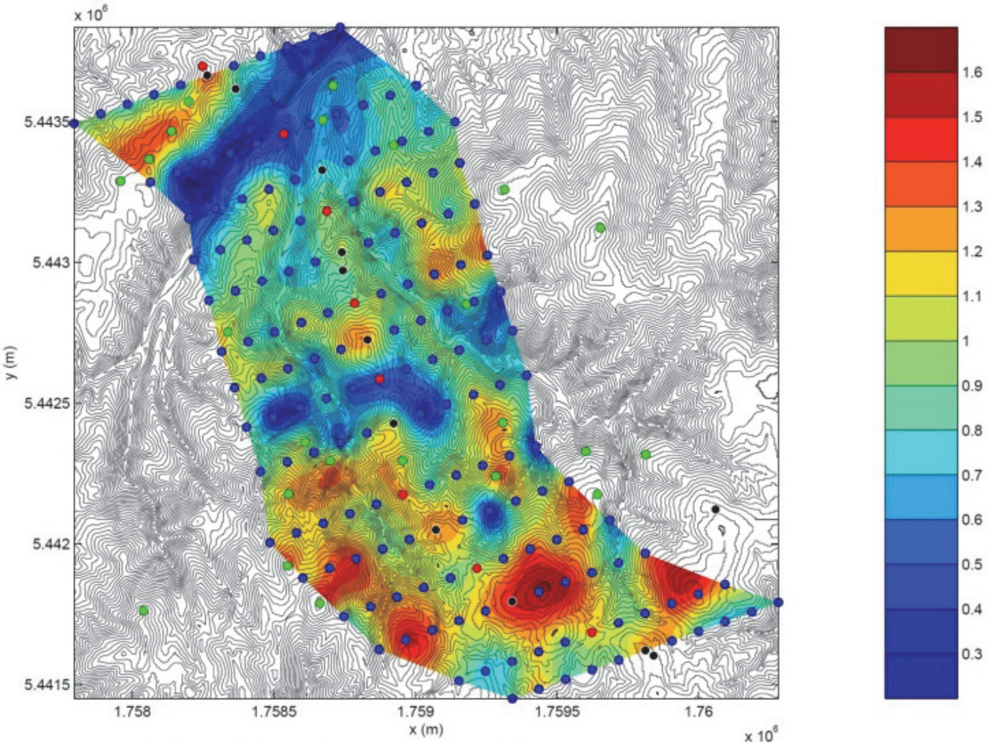


Fig. 11. Colour contour plot of the gust hill shape multipliers measured in the wind tunnel for a wind direction of 340° at 10 m height shown superimposed on a topographical contour map of the area.

direction of 340° at a height of 10 m, within the area of the regular grid, and is superimposed on a topographical contour map. Whilst somewhat hard to see, it is evident that the highest gust speedups occur near the tops of hills, and the lowest values occur in the valleys.

Comparison of Speed-up Results from all the Methods

The results compared here are the hill shape multipliers for the nine anemometer locations Met1 to Met9 at 5 m above ground level for a wind direction of 345°. The results from full-scale observations, the wind tunnel, CFD (WASP and Gerris) and AS/NZS1170.2 are listed in Table 2.

The gust speedups from the full-scale, Gerris and wind tunnel results show good agreement, whereas the agreement with the results from WASP is not so good and the predictions from the standard AS/NZS1170.2 are worse still. It was found that the agreement between full-scale, Gerris and wind tunnel was slightly better for the gust hill shape multipliers than for the mean hill-shape multipliers. This may be explained by the fairly flat distribution of STD over the various masts – so the estimated maximum wind gust (mean + 3.7* STD) speedups are in essence a smoothed version of the mean speedups. The agreement is also better for the anemometers with significant speedup over the hill (anemometer locations 1,2,3,5,9) compared to the anemometers which have small speedup or are in more sheltered locations (anemometer locations 4,6,7,8). The insensitivity of the loadings standard estimates at hill tops compared to valleys and the large variations between the NIWA and UoA calculations is of concern and is discussed further in the next section.

Table 2. Comparison of gust hill shape multipliers at a height of 5 m above local ground level for the nine anemometer locations Met1 to Met9 for a wind direction of 345°.

Met Anem No.	1	2	3	4	5	6	7	8	9
Full-scale Obs	1.46	1.66	1.35	1.05	1.25	1.00	0.84	0.81	1.31
CFD Gerris	1.36	1.57	1.37	1.17	1.33	1.11	0.97	0.88	1.29
Wind Tunnel	1.33	1.56	1.34	1.07	1.31	1.04	0.80	0.93	1.44
WASP	1.26	1.72	1.26	0.85	1.47	1.03	0.74	1.15	1.72
1170 NIWA	1.20	1.43	1.35	1.36	1.52	N/A	N/A	1.10	1.14
1170 sea flat (UoA)	1.10	1.09	1.08	1.07	1.06	1.06	1.05	1.04	1.03
1170 valley flat (UoA)	1.08	1.06	1.05	1.03	1.01	1.00	1.00	1.00	1.23

Vertical Variation of Hill-shape Multipliers and Matching to AS/NZ1170.2

As discussed earlier, wind tunnel speedup measurements were obtained at model heights equivalent to full-scale heights of 5 m, 10 m, 20 m, 50 m, 100 m, 200 m, and 500 m at the locations of the anemometers for wind directions of 340° and 360°. Linear interpolation was used to estimate the speedups for a wind direction of 345°. Values for mast Met5 are given in Table 3.

Table 3. Gust speed-ups from wind tunnel measurements for mast location Met5

height (m)	5	10	20	50	100	200	500
WT speedup	1.31	1.28	1.17	1.10	1.05	1.02	1.01

It is instructive to investigate what slope is necessary in order for the wind loading standard to give the same speedup as measured in the wind tunnel. It can be shown from Eq (1) that the speed-up at the crest of a hill is related to the slope, *s* by the relationship,

$$M_h = 1 + s * 1.59 \tag{2}$$

If it is assumed that the gust speedup for a height of 5 m approximates that at ground level, then the slope necessary to achieve the speedup of 1.31 obtained in the wind tunnel can be found from Eq (2).

$$s = \frac{M_h - 1}{1.59} = \frac{1.31 - 1}{1.59} = 0.2 \tag{3}$$

This is a much higher slope that the actual slope. Furthermore, if the measurement station is upwind of the crest, then the slope must be higher to get the same speedup.

It would appear that it is only possible to achieve such high slopes by considering localised features of the hilly terrain. The speedup can be recalculated on this basis. Consider only the upwind distance of approximately 800 m for the present hill for mast Met5. Over this region the slope is 0.19. Furthermore, assume that Met5 is on the crest of a "local" hill, so that for this location, $x = 0$, the hill height $H = 150$ m and $L_u = 394$ m. Using the procedures outlined in AS/NZS1170.2, (2011), it can be shown that $M_h = 1.29$, which is very close to the wind tunnel value of 1.31. Speed-ups using this approach have been calculated for the same heights as for the wind tunnel measurements and are shown in Fig. 12 with speedup values for the same heights assuming the "sea flat".

The results in Fig. 12 are very interesting and show that although using the local hill slope in the AS/NZS1170.2 approach works well for very low heights, it does not work well above a height of 10 m, when it begins to considerably overestimate the speed-up. The predictions from the standard which assume that the hill goes all the way to the sea show better agreement with the wind tunnel for moderate heights around 50 to 200 m, but this approach also overestimates the speedup for larger heights. Note that it is rare that buildings and structures in New Zealand exceed a height of 150 m, and so perhaps such overestimation is not important, and certainly it is conservative. Thus it is evident that the formulaic approach in the standard works satisfactorily for heights around 100 m, but it does not capture well the large reduction in speedup that occurs with increasing height that is clearly evident from the wind tunnel results.

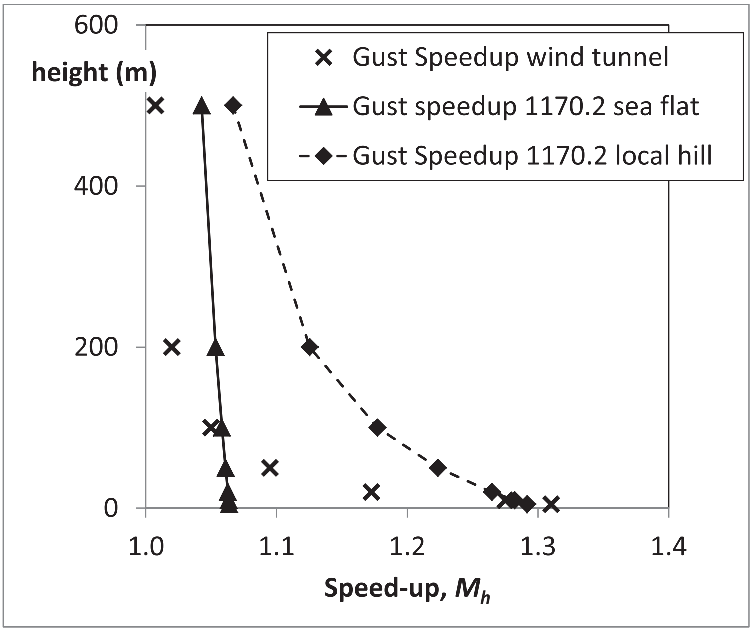


Fig. 12. Gust speedups calculated using AS/NZS1170.2 assuming:(1) the hill starts at the sea;(2) that the hill is a local feature, compared with wind tunnel measurements.

Discussion of Results

In order to attempt to answer the question – "How good is the AS/NZS 1170.2 loadings standard at estimating wind speed-up over hills in rugged terrain?"– observed speedups in the Belmont Regional Park near Wellington have been compared with speedup estimates based on: the AS/NZS1170.2 standard, the CFD models WASP and Gerris, and the OPUS wind tunnel. Figs. 13 and 14 combine the results for speedups from all methods for means and gusts respectively. Fig.

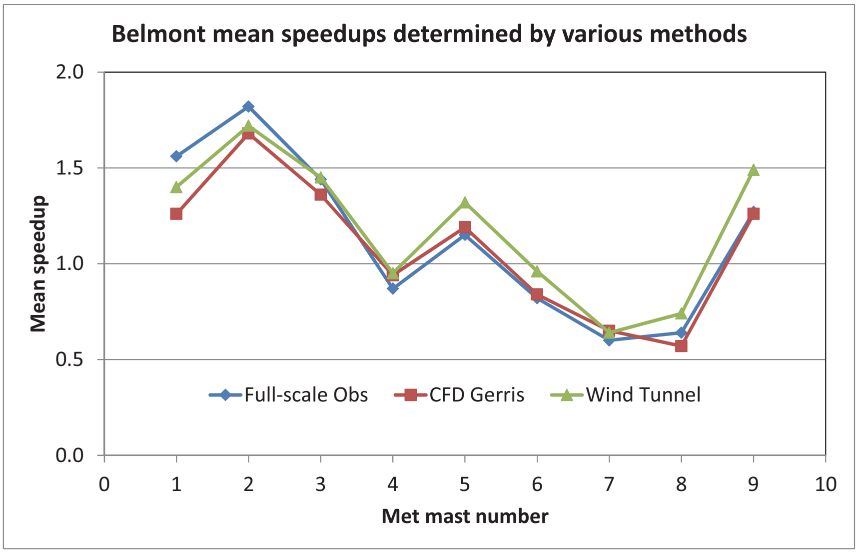


Fig. 13. Mean speedups at a height of 5 m at each mast location for a wind direction of 345° from observations (blue), the CFD code Gerris (red) and the wind tunnel (green).

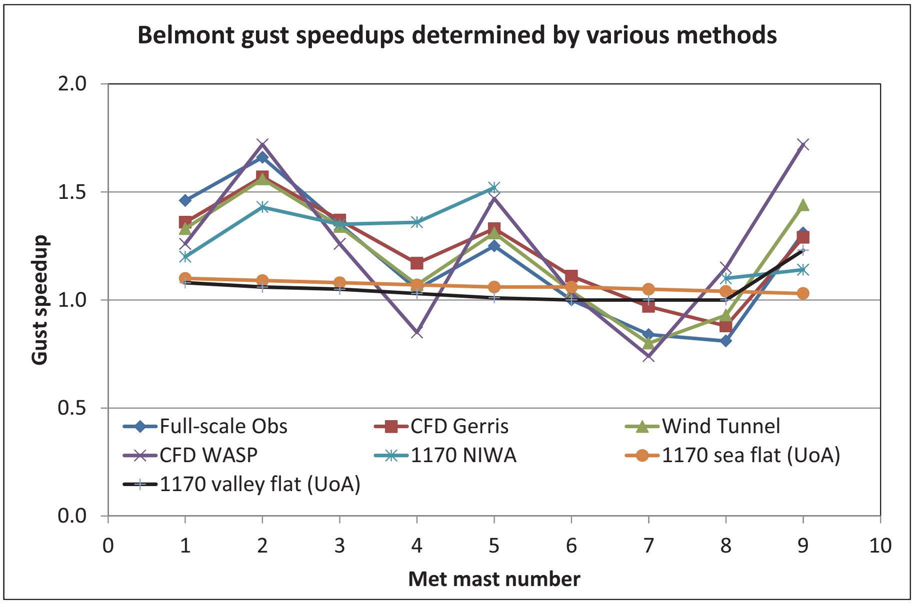


Fig. 14. Gust speedups at 5 mheight for a wind direction of 345° from observations (dark blue), CFD Gerris (red), wind tunnel (green), WASP (purple), AS/NZS1170 NIWA (light blue), AS/NZS1170 sea flat UoA (orange) and AS/NZS1170 valley flat UoA (black).

13 clearly shows good agreement in the speed-ups of the means from the observations, CFD code Gerris, and the wind tunnel measurements. These three approaches also show good agreement for the gust speedups in Fig. 14, but there are clearly larger differences with the CFD code WASP and the AS/NZS1170.2 estimates of speedup. Possible reasons for this result are discussed below. It was found that in this complex and rugged Belmont Hill region terrain, where shedding of eddies by upstream hills is likely to have an important influence on windspeeds, and the presence of valleys and ridges along the wind direction further complicates the picture, CFD modelling with Gerris or scale modelling with a wind tunnel differentiates very well between the regions where the flow is sped up and slowed down. Results are within 15% and frequently within 5%. A simple potential flow solution with some adjustment for roughness changes using WASP gives less accurate results – tending to over-estimate both the speedups and sheltering. For low heights of 5 m or so, the loadings Standard AS/NZS 1170.2 struggles to differentiate as well between sheltered and exposed sites at scales less than 500 m due to the requirement for fitting the hill to 500 m long straight line segments, and appears to produce variable estimates of design winds depending on the assumptions made by the person carrying out the calculations. However, when results from the standard are compared with wind tunnel results at much larger heights, it appears to perform much better, especially for heights around 100 m. Nonetheless, irrespective of whether the method in the standard uses local values or extensive values for determining slopes, it does not appear to correctly predict the rather large reduction in speedup with height that is evident from the wind tunnel measurements. Perhaps the approach in the standard needs to be modified so that the surrounding fetch that is considered in the slope calculations scales with the height of interest, like the upwind fetch used to calculate the average terrain roughness.

Unfortunately, modelling a given site with Gerris or a wind tunnel is more expensive (roughly twice the cost) than applying WASP and considerably more expensive (roughly ten times the cost) than applying the Loadings Standard (costing a few hundred dollars for a single site calculation).

In terms of practical advice for someone wanting to estimate a design wind speed in a remote location with rugged topography in New Zealand, the following comments are made. The loadings standard generates a result for a single point whereas the wind tunnel and CFD methods generate values over a large 10 km x 10 km square area at better than 50 m resolution – potentially for many points. For an isolated single location it may be less expensive and more convenient to apply the loadings standard, but because of the potential inaccuracies in the method, it may be necessary to be conservative (apply an over-estimate of the wind speedup). Depending on the size of the proposed structure this may lead to a considerably larger building cost – potentially far outweighing the extra cost in estimating the wind speed more accurately. If estimates at many (more than 10) locations are required in a given 10 km x 10 km square area then it will almost certainly be more cost effective to use a CFD- or wind tunnel-based method.

Recommended Future Research on Hill-shape Multipliers (Wind Speed-up)

It should be noted that the results presented and discussed in the paper are based on one eighteen-hour period of strong winds from a specific direction at a single location. The authors are continuing research on wind speed-up in order to confirm the relative merits of the various methods for other locations and wind directions.

The Belmont experiment is expected to provide useful information to the RiskScape project (King *et al.*, 2008 and King and Bell, 2009). One of the aims within RiskScape is to develop an impact/risk forecast by using NIWA's weather and environmental forecasting system (EcoConnect) to feed wind maps (speed and direction) into RiskScape which will allow forecast estimates of possible damage from an imminent storm. However, loss modelling requires high resolution wind data, whereas present routine weather forecast calculations are only available on a 1.5 km grid. The required high resolution speed-up maps could be generated by either "downscaling" the forecast through the Gerris model or by using a multiplier approach. The present

Belmont wind speedup research projectd has provided useful calibration data for Gerris over typical New Zealand complex terrain for this purpose.

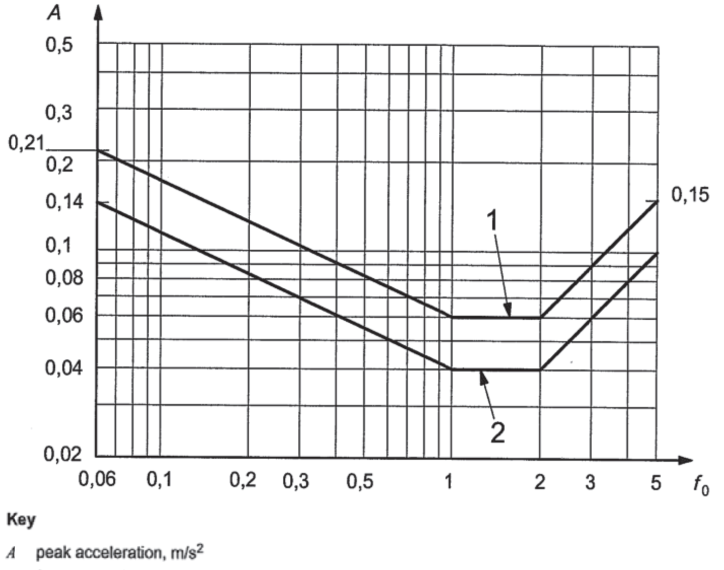
It is very evident from this research project that AS1170.2 could undergo some improvement in its prescriptive method used for determining wind speed-up. This is because the present approach has been shown to produce different speedups from different people and organisations. Since the speedup factor can potentially be rather large (1.71 for a hill of slope of 0.45) there is a significant potential for either conservative or non-conservative design loads. Hence it is recommended by the authors that New Zealand provide support to enable further research in this area so that the potential errors in such predictions are reduced. This will ultimately provide economies for the construction industry, as structures and buildings will be designed to withstand more closely the imposed with loads to which they are likely to be exposed over their life.

Part 2: Monitoring of Wind-induced Tall Building Motion in New Zealand

This section of the paper describes the results of monitoring the wind-induced motion of tall buildings in New Zealand between 2009 and 2012: four in Wellington and one in Auckland. The monitoring has been undertaken as part of a research programme to develop an improved methodology for the design of buildings, to ensure that wind-induced motion of new tall buildings remains within acceptable limits. Aspects of this research have been described in previous papers [Carpenter *et al.* (2011), Carpenter *et al.* (2012), Carpenter *et al.* (2013a), Carpenter *et al.* (2013b)].

Acceptability Criteria for Building Motion

The ISO provides guidance [ISO Standard 10137 (2007)] for human response to wind-induced motions in buildings. It indicates that peak accelerations should not exceed the basic evaluation curve for the respective occupancy. There are separate curves for offices and for residences, with the limits for residences being 2/3 of those for offices. The ISO figure is reproduced in Fig. 15. The



1 Offices 2 Residences

Fig. 15. ISO 10137: 2007 Evaluation curves for wind-induced vibrations in buildings in a horizontal direction for a one-year return period. (Note that in Fig. 15, the accelerations are given in m/s2, however, milli-g are mainly used elsewhere in the paper.)

ISO limits in the frequency range 1 to 2 Hz are approximately 6.1 milli-g for offices and 4.1 milli-g for residences.

Kwok (2009) has discussed the ISO criteria in comparison with other published criteria, and indicated that they are at the low end of the range.The ISO standard specifies that both translation and torsion should be considered in applying the criteria. However, it is not clearly specified in the standard whether these should be considered separately or combined. If the effects of translation and torsion are combined, then the analysis is essentially concerned with the accelerations at the corners of the top floor of the building. If translation and torsion are considered separately, then the analysis is concerned with the accelerations on the whole of the top floor.

In view of the observation by Kwok that the ISO criteria are the lower end of the range of acceptability criteria, it is suggested that translation and torsion should be considered separately in this analysis of building motion and comparison with the criteria, rather than considered together. The practical effect of this is that translation accelerations alone are on average about 30% less than the combined accelerations, and therefore the building is less likely to exceed the criteria when the accelerations are considered separately. This suggestion is also based in the knowledge that none of the measured buildings were reported to the authors as experiencing excessive wind-induced motion.

Buildings Selected for the Study

Two of the buildings which have been analysed are part of the New Zealand GeoNet project. The instrumentation was not specifically installed for the wind motion research. It was fortunate that data from these buildings became available for inclusion in this study.

Three of the buildings were specifically chosen by Opus and University of Auckland for wind motion research. The factors which were considered in selecting these buildings were as follows:

- Two buildings in Wellington were chosen, primarily due to the high proportion of windy conditions in Wellington.
- One building in Auckland was also selected, to provide a wider geographical spread of buildings.
- Some New Zealand buildings have been reported as having high or uncomfortable motion in strong winds. A decision was made not to focus on these buildings, but to study representative tall buildings which could have wind-induced motion at around the acceptability criteria limits. Consequently, none of the buildings that were studied had been previously reported as having detectable wind-induced motion.
- The equipment was located on the building roofs, where it would not typically be noticeable to building users. Buildings with sloping roofs, or with roofs where access was unsafe were therefore unsuitable.
- Relatively modern buildings were chosen, less than 20 years old.
- Some building owners decided that there was a risk of adverse publicity if it became known that their buildings were being investigated for wind-induced motion, and therefore declined our request for access. Consequently, the authors made it standard practice in their approach to building owners, to state that the buildings would not be named in publications arising from the research.

Description of the Buildings

The five buildings which have been analysed are referred to as Buildings A, B, C, D and E, which are listed in the order that monitoring commenced.

- Building A is in Wellington. It is 10 storeys high, with a rectangularplanform, and a steel frame structure. Monitoring as part of the New Zealand GeoNet project has been on-going since early 2009.

Table 4. Measured X, Y and Torsion frequencies for the five buildings

Building	X direction	Y direction	Torsion
A	1.56 Hz (~EW)	1.42 Hz (~NS)	2.10 Hz
B	0.55 Hz (~NS)	0.54 Hz (~EW)	0.84 Hz
C	0.63 Hz (~NS)	0.65 Hz (~EW)	0.65 Hz
D	1.09 Hz (~NS)	0.79 Hz (~EW)	1.41 Hz
E	0.44 Hz (~NS)	0.46 Hz (~EW)	0.68 Hz

- Building B is in Wellington. It is 25 storeys high, with an approximately square planform, and has a structure consisting of concrete perimeter columns with a central core. It was monitored by Opus during the period from 21 August 2009 to 15 October 2009.
- Building C is in Wellington. It is 17 storeys high, with an approximately square planform, and has a concrete structure including a wall on one side, and an offset core adjacent to the concrete wall. It was monitored by Opus during the period from 21 October 2009 to 22 February 2010.
- Building D is in Auckland. It is 25 storeys high, with a rectangular planform, and has a concrete structure. It was monitored by Opus during the period from 20 October 2010 to 27 May 2011.
- Building E is in Wellington. It is 28 storeys high, and has a concrete structure. Monitoring as part of the New Zealand GeoNet project has been on-going since early 2012.

Multiple modes of vibration have been identified for each building through analysis of the motion time histories. The measured X, Y and Torsion frequencies for each building are listed in Table 4. A notable feature of these measured frequencies is the low torsion frequency of Building C. The frequencies in all three directions are similar, and the frequencies in the Y direction and in torsion are the same, indicating that the building oscillates with coupled mode response.

Instrumentation

Buildings A and E have been instrumented as a part of the Geonet Building Instrumentation Programme funded by the New Zealand Earthquake Commission (EQC). This is a long-term programme that aims to install earthquake strong-motion instruments in up to 30 structures across New Zealand. The equipment is set up for earthquake monitoring, recording at a rate of 200 Hz, with limitations on its ability to record continuously. The consequence of this is that much less statistical data were available for the analysis of Buildings A and E, compared to Buildings B,C, and D.

The instrumentation in Buildings B, C and D was installed by Opus. The recording was continuous, typically at a rate of 25 Hz. The two accelerometers were mounted at diagonally opposite corners of the roof, which enabled the X, Y and torsion modes of vibration of the building to be measured. The anemometer was located at a height of 2.5 m above the roof at the windward corner of each building for the most common wind directions. This was the NW corner for buildings B and C, and the SW corner for Building D. These locations meant that the anemometer was sheltered by the building for the other less common wind directions. Only data for northerly winds have been included in the analysis for buildings B and C in this paper, and only data for westerly winds have been included in the analysis for building D.

The height of the anemometer was less than ideal for measurement of the reference wind speed, but provided an adequate measure of the variation in wind speed for the most common wind directions. The reasons that a taller anemometer pole was not used included:

- It was necessary to comply with the city planning rules concerning the heights of structures on the building roofs.
- A short pole was simple and safe to install.

- The authors wanted to avoid drawing any attention to the monitoring being done on the building, or causing any difficulties for the building owners.

Data Analysis

Table 5summarisesthe accelerations measured during each single biggest building-motion event. The most extensive data were obtained for Buildings C and D.

Table 5. Summary of accelerations measured during the single biggest building-motion event for each building.

	Building				
Measured	**A**	**B**	**C**	**D**	**E**
X direction at centre of building (milli-g)	2.1	1.1	1.8	0.6	3.2
Y direction at centre of building (milli-g)	3.2	2.9	3.0	1.3	4.3
Combined XY at centre of building (milli-g)	3.3	2.9	3.6	1.3	4.4
Acc'n at the corners due to torsion (milli-g)	2.3	0.7	3.6	0.5	2.9
Corner (max acc'n at either corner) (milli-g)	3.6	3.2	5.8	1.7	6.2
Amplitude at centre of building (mm)		5.4	3.8	1.2	10.5
Date (2009)	23 May	26 Aug	08 Jan	18 Apr	8 Sept
Airport mean wind speed (m/s)	23	16	14	14	18
Airport wind direction	210	300	340	240	340

Notes:
1. Accelerations in torsion are measured at the corners of the building, relative to the centre of the building.
2. Wellington reference wind speed was measured at Wellington Airport. Auckland reference wind speed was measured at Whenuapai Airport.

Relationship Between wind Speed and Acceleration

The relationship between the wind speed measured on the roof of the building, and the acceleration at the centre of the roof of the building, has been analysed for Buildings B, C and D. The best correlation was obtained from the so-called "effective wind speed" measure of wind speed, which is the average of the 1-hour mean wind speed and the maximum gust speed in the hour. Some measures of the wind speeds closer to the building motion event were also included in the analysis, including the 100 s mean wind speed, the 10 s mean wind speed, and the maximum wind speed during the 100s. The correlation with the measured accelerations was examined for all these wind speed measures. It was notable that the two wind speed measures for the whole hour (the mean and the maximum) produced substantially better correlations than the other measures, and the best correlation of all was achieved using the average of the 1-hour mean and the 1-hour maximum. For Building C the data have been analysed for all hours when the 1-hour mean wind speed at the building for northerly winds exceeded 7 m/s; there were 535 hours of data in this category for Building C. The resulting plot is shown in Fig.16. The data have been further analysed by averaging the measured accelerations into bands, as shown in Fig.17. In Figs. 16 and 17 Veff is the average of the hourly mean and the maximum gust in the hour.

There was a very good power-law fit to the band-averaged data for all three buildings. The exponents of the power-law fit calculated from the band-averaged data are: Building B:2.89, Building C: 3.10, Building D:3.18.

For the three buildings combined, the average exponent of the power-law fit is 3.06. The measurements consequently confirm the expectation that the exponent would be close to 3 for these buildings, as proposed by Cenek et al, (1989), and discussed further by Carpenter et al, (2011).

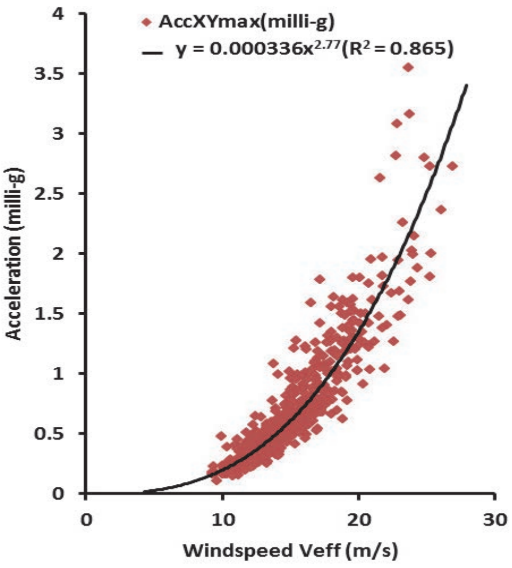


Fig. 16. Building C. Relationship between windspeed and acceleration.Northerly wind, Vmean> 7 m/s

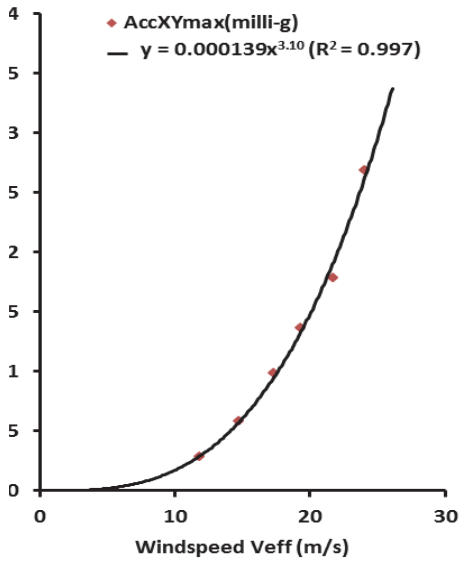


Fig. 17. Building C. Relationship between wind speed and acceleration. Same data as Fig. 16, but averaged into acceleration bands.

Building Acceleration Prediction Equations

The 1990 BRANZ study [Cenek and Wood, (1990)] led to the derivation of a simple equation for prediction of building motion [Cenek *et al.*, (1989)], given here as Eq. (4).

$$a = \frac{0.46\overline{V}(h)^3}{fm_0} \tag{4}$$

where

$\overline{V}(h)$ = mean hourly wind speed at the top of the building (m/s)
f = fundamental frequency (Hz)
m_0 = $\rho_b A$ = mass per unit length over the top one third of the structure (kg/m)
a = peak resultant acceleration (m/s^2)
ρ_b = building density (kg/m^3)
A = building plan area (m^2)

Prediction of Annual Maximum Building Motion

A statistical analysis of the largest building motion events for each building has been applied to predict the motions for a 1-year return period. These are listed in Table 6, which also lists the ISO 10137 limits for each building, and predicted accelerations calculated using Eqn (4). It can be seen that building C exceeds the ISO limit by about 20% at the centre of the building. This building has a coupled mode response which contributes to the higher measured accelerations. The other four buildings are within the ISO limits.

Fig.18 plots the relationship between the estimated annual maximum combined XY accelerations from the measured data compared to the accelerations predicted using equation (4). The best fit line through the data indicates that the prediction, on average, under predicts the measured data by 12%. It is reassuring to find that one of the tools that have been applied in NZ for

Table 6. Predictedannual maximum accelerations

	Building				
Estimated annual maximum accelerations	**A**	**B**	**C**	**D**	**E**
Combined XY at centre of building (milli-g)	3.2	5.4	9.0	3.0	4.4
Torsion (milli-g)	2.1	1.9	8.2	1.3	2.2
Corner (maximum acceleration at either corner) (milli-g)	4.4	6.5	15.4	3.6	5.7
ISO 10137 limit (milli-g)	4.1	8.0	7.5	4.6	8.8
Predicted accelerations calculated using Eqn(4) (milli-g)	3.8	4.1	5.4	5.0	5.5
Predicted accelerations calculated using Eqn(5) (milli-g)	4.2	4.4	6.0	5.5	5.6

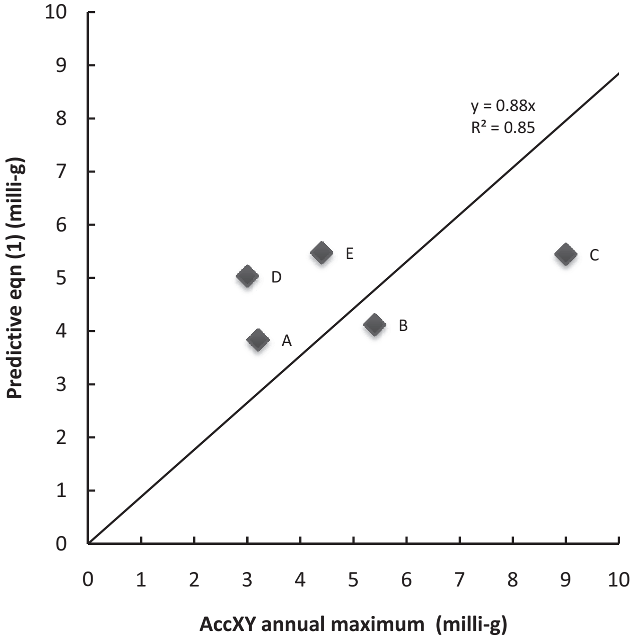


Fig. 18. Relationship between measured and predicted accelerations using equation (4)

many years provides results which are so close to the measured accelerations of these real buildings.

Revised Building Acceleration Prediction Equation

The prediction equation from Cenek *et al.*, Eq(4),developed in 1989 uses1-hour mean wind speeds in the analysis, which was consistent with the wind speed required for the dynamic analysis procedures in the wind loading standard at that time. In 2002 the Australia/New Zealand Standard was changed to use gust wind speeds. Using the results presented in this paper Eq(4) can now be revised to use the gust speed, and to correct for the small 12% average under-prediction that is evident in Fig. 18 and Table 6 from the present measurement programme. The revised equation is

$$a = \frac{0.113 V_{des,1-year}^{3}}{f m_0}, \tag{5}$$

where$V_{des,1\text{-}year}$ is calculated using the loading standard (AS/NZS 1170.2, 2011).

Predictions of accelerations from this equation are given in Table 6 where it can be seen that it gives slightly better predictions of accelerations than Eq(4).

Conclusions to Parts 1 and 2

In Part 1 of the paper it was found that in this complex and rugged Belmont Hill region terrain, where shedding of eddies by upstream hills has an important influence on the windspeeds, and the presence of valleys and ridges along the wind direction further complicates the flow regime, CFD modelling with Gerris or scale modelling with a wind tunnel differentiates very well between the regions where the flow is sped up and slowed down at the low measurement height of 5 m. Results are within 15% and frequently within 5%. A simple potential flow solution with some adjustment for roughness changes using WASP gives less accurate results – tending to overestimate both the speedups and sheltering. For the low height of 5 m, the loadings Standard AS/NZS 1170.2 struggles to differentiate as well between sheltered and exposed sites at scales less than 500 m due to the requirement for fitting the hill to 500 m long straight line segments, and appears to produce variable estimates of design winds depending on the assumptions made by the person carrying out the calculations. However, when results from the standard are compared with wind tunnel results at much larger heights, its performance is much better, especially for heights around 100 m. Nonetheless, irrespective of whether the method in the standard uses local values or global values for determining slopes, it does not appear to correctly predict the rather large reduction in speedup with height that is evident from the present wind tunnel investigation. Perhaps the approach in the standard needs to be modified so that the surrounding fetch that is considered in the slope calculations scales with the height of interest, like the upwind fetch used to calculate the average terrain roughness in the standard.

The secondsection of the paper describes the results of monitoring the wind-induced building motion of five tall buildings between 2009 and 2012, four in Wellington and one in Auckland. The buildings were selected to be fairly representative of tall buildings in New Zealand; buildings which are known to experience high accelerations were not selected for the study. The measured accelerations were compared with acceptability criteria from ISO Standard 10137:2007. The accelerations were within the acceptability criteria for four of the buildings, and exceeded the criteria by about 20% for the fifth building. The relationship between wind speed and acceleration was examined for three of the buildings. The measured wind-induced accelerations were found to be approximately proportional to the cube of the wind speed. This demonstrates that accurate estimation of the wind speed is critical in order to make accurate design predictions of wind-induced building motions. A simple predictive equation has been described andshown to give reasonable estimates of the expected annual maximum building motion.

Acknowledgements

The success of the Belmont Hill wind speed-up study has shown the benefits of collaborative research effort, in this case between NIWA, GNS, Opus, and the University of Auckland. The authors would like to thank the following people and organisations: Tony Bromley and Ross Martin at NIWA for setting up equipment, making measurements, liaising with landowners; Sylvia Nichol at NIWA for making the AS/NZS 1170.2 loadings code calculations; Callum Murton at Opus for making the wind tunnel measurements; DOC & GWRC for allowing access to land and mast data; Mostafa Nayyerloo and SR Uma of GNS Science for reviewing the research report; The New Zealand Foundation for Research, Science and Technology for supporting this work under the Natural Hazards Research Platform via Contract 2010-GNS-04-NHRP.

The building motion measurement study was a collaborative programme involving Opus, the University of Auckland, and GNS. The primary research was funded by the Building Research Association of New Zealand. The authors acknowledge the New Zealand GeoNet project and its sponsors EQC, GNS Science and LINZ, for the data used in this study. The authors are grateful to the building owners who allowed the measurements to take place in their buildings.

References

Australia/New Zealand Standard AS/NZS1170.2.(2011), Structural design actions. Part 2: Wind actions,Jointly published by Standards Australia International Ltd and Standards New Zealand.

Bowen, A.J. and Lindley, D. (1977).“A wind tunnel investigation of the wind speed and turbulence characteristics close to the ground over various escarpment shapes”, Boundary Layer Meteorology, 12 259-271.

Bowen, A. J. and Lindley, D. (1974), “Measurement of the mean wind flowover various escarpment shapes”, Proc. of the 5th AustralasianConference on Hydraulics and Fluid Mechanics, 211-219, Univ.of Canterbury, Christchurch, N.Z., December.

Carpenter, P. (1990), “Wind speeds in city streets - full scale measurements and comparisons with wind tunnel tests”, in Recent Advances in Wind Engineering, 2ndAsia Pacific Symposium On Wind Engineering, Beijing, China, Pergamon Press, New York.

Carpenter, P., Cenek, P.D., Flay, R.G.J.(2011),“Monitoring of wind-induced building motion”, Proc. of the13th International Conference on Wind Engineering, ICWE13, Amsterdam, 10-15 July.

Carpenter, P., Cenek, P.D., Flay, R.G.J.(2012),“Monitoring of wind-induced motionof tall buildings in New Zealand”, Structural Engineering Society New Zealand, SESOC Conference, Auckland, 2-3 November.

Carpenter, P., Cenek, P.D., Flay, R.G.J.(2013a),“Monitoring of wind-induced motionof tall buildings”, Proc. of the 6th European African Conference on Wind Engineering, Cambridge, UK, 7-11 July.

Carpenter, P., Cenek, P.D., Flay, R.G.J.(2013b),“Monitoring of wind-induced buildingmotionand comparison with wind tunnel measurements”, Proc. of the 16thAustralasian Wind EngineeringSociety Workshop,Brisbane, Australia, 18-19 July.

Carpenter P., Murton C., Cenek P. (2011),Simulated wind flow measurements over hill terrain, Opus Central Laboratories Report 11-529B50.

Carpenter, P., Reid, S.(1990), Aspects of the Assessment of Design Wind Speeds for Building Sites in New Zealand, Opus Report 90-29116.

Cenek P.D., George S., Wood J.(1989),Designing for building dynamic serviceability under wind loading. Proc. of the 2nd Asia Pacific Symposium on Wind Engineering, Beijing, China, 1989.

Cenek, P.D., Wood,J.(1990), Designing multi-storey buildings for wind effects under wind loading. BRANZ Study Report No 25 (1990).

Chiappini, C. and Flay,R.G.J. (2004),“Comparison of wind tunnel prediction techniques for pedestrian level winds with full-scale measurements”, 11th Australasian Wind Engineering SocietyWorkshop, Darwin, Australia, June.

Cherry, N.J. (1980), “Wind energy resource survey methodology”, J. of Wind Eng&Indust.Aerod., 5, 247-280.

Edwards, P.J. (1990), “Wind energy resource studies in New Zealand,” Solar & Wind Technology, 7(1), 9-14.

Feasey, R. and Freeston, D.H. (1977), “Wind pressure measurements on a multi-storey building”, 6th Australasian Hydraulics and Fluid Mechanics Conference, Adelaide, South Australia, 5-9 December.

Flay, R.G.J., Stevenson, D.C., and Lindley, D. (1982), “Wind structure in a rural atmospheric boundary layer near the ground”, J. Wind Eng& Ind. Aerody. 10(1), 71-81.

Flay R.G.J., Turner R., Revell, M., Carpenter P., Cenek, P., King, A. (2011),“The potential wind hazard of wind speed-up over hills and complex terrain, and the risk to infrastructure”, Proceedings of the 7th APRU Research Symposium on Multi-hazards around the Pacific Rim, Auckland, November.

Flay, R.G.J., Turner, R., Revell, M., Carpenter, P., Cenek, P., King, A. (2012),“Wind speed up over hills and complex terrain, and the risk to infrastructure”, Proceedings of the 18th Australasian Fluid Mechanics Conference, Launceston, Australia, 3-7 December.

Flay, R.G.J., Turner, R., Revell, M., Carpenter, P., Cenek, P., King, A.B. (2013),“Wind speed-up over Belmont Hill in complex terrain”,Proceedings of the 6th European African Conference on Wind Engineering, Cambridge, UK, 7-11 July.

International Standard ISO 10137, (2007) (E).Bases for design of structures – Serviceability of buildings and walkways against vibrations.ISO.

Jackson, P.S. (1976), The Thorndon wind tower project- Part 1 Data collection, Central Laboratories, Ministry of Works and Development.Available from NIWA Library, Wellington.

Jackson, P. S., Hunt, J. C. R. (1975),“Turbulent wind flow over a low hill”, Quart. J. R. Meteor. Soc., 101, 929-955.

King, A.B., Cousins, W.J., Heron, D.W., Maitcham, I., Pringle, R., Bell, R., Reese, S., Schmidt, J., Henderson, R. (2008),“Regional RiskScape: a multi-hazard loss modelling tool”, in4th International i-Rec Conference 2008: building resilience: achieving effective post-disaster reconstruction: conference papers and presentations. Christchurch, NZ: i-Rec, 11 p.

King, A., Bell, R. (2009),RiskScape Project 2004-2008, GNS Consultancy Report 2009/247, 162pp.

King, A.B., Revell, M., Carpenter, P., Turner, R., Cenek, P. and Flay, R.G.J. (2012), Modified wind speed due to topographic effects, GNS Science Report 2012/07. 34 p.

Kwok K.C.S., Hitchcock P.A., Burton M.D.(2009),“Perception of vibration and occupant comfort in wind-excited tall buildings”, J. of Wind Eng. and Ind. Aerod., 97, 368–380.

Meroney, R. N., Lindley, D., and Bowen, A. J. (1979). "Physical modelling of flow over complex terrain", Proceedings of Fifth International Conference on Wind Engineering, Colorado State University, Fort Collins, Colorado, July 8-14, 975-985.

Neal, D. (1982), "Full-scale measurements of the wind regime over a saddle, and correlation with wind–tunnel tests", Boundary Layer Meteorology, 22(3), 351-371.

Popinet, S. (2003),"Gerris: a tree-based adaptive solver for the incompressible Euler equations in complex geometries", J. Comput. Phys., 190, 572-600.

Popinet, S., Smith, M., Stevens, C. (2004),"Experimental and Numerical Study of the Turbulence Characteristics of Airflow around a Research Vessel", J. Atmos. and Oceanic Technology, 21, 1575-1589.

Raine, J.K. and Stevenson, D.C. (1977), "Wind protection by model fences in a simulated atmospheric boundary layer", J. Ind. Aerodyn., 2, 159-180.

Reese, S., Revell, M., Turner, R., Thurston, S., Reid, S., Uma, S.R., Schroeder, S. (2007),Taranaki Tornadoes of 4-5 July 2007: Post event damage survey, NIWA report WLG2007-71, 43 pp.

Reid, S.J.(1987),"Wind speeds for engineering design", New Zealand Engineering, 42(2), 15-18.

Reid, S., Turner, R. (2004),Severe winds near Molesworth on 9 January 2004, NIWA report WLG2004-63. 16 pp.

Revell, M., Popinet, S., Reese, S. (2009),"Downslope winds – an explanation for roof damage in Cobden, Greymouth in July 2008", Paper presented at the joint New Zealand Meteorological and Marine and Freshwater Societies conference at the University of Auckland, September.

Richards, P. J.(1986), "Wind protection in the vicinity of right angle wind break corners", Proc. of the 9th Australasian Fluid Mechanics Conference, Auckland, December, 193–195.

Troen, I., Petersen, E.L. (1989),"European Wind Atlas", ISBN 87-550-1482-8. Risø National Laboratory, Roskilde. 656pp.

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Wind comfort predictions by wind tunnel tests: comparison with full-scale data

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Abstract

Two studies were carried out in order to acquire more knowledge on the reliability of the method used by TNO to predict the wind climate around buildings. The first was a complex situation of a relatively low building in a complex environment of wooded areas and trees. The second related to the results of full-scale measurements at the base of a high-rise building under construction and a comparison with wind tunnel testing. It is found that the wind tunnel method generally gives a reliable prediction of the full-scale wind climate, both for low and high-rise buildings and for situations with and without vegetation. The wooded areas and trees around the low building complex were simulated with pieces of gauze with a permeability of 57%. This simulation is in good agreement with the winter period. The agreement with the summer period is less good. However, because of the frequency distribution of high wind velocities over the seasons, this simulation also gives a sufficiently reliable approximation of the yearly averaged wind climate.

1. Introduction

It is well known, that high-rise buildings can create high wind velocities at ground level, resulting in wind discomfort or even dangerous situations for pedestrians and cyclists. The possible occurrence of wind discomfort or wind danger is usually predicted by means of wind tunnel tests. In addition, the wind tunnel may be used as a useful tool for finding ways of improving the situation. For almost twenty years, wind comfort studies have been carried out in the atmospheric boundary-layer wind tunnels of the Fluid Dynamics Department of IMET-TNO. The method consists of wind tunnel measurements by means of simple omnidirectional thermistor probes and coupling of the wind tunnel data with the wind statistics of a representative

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meteorological station. Neither the whole method nor parts of the method have ever been validated. It was therefore decided in 1986 that an investigation should be started on the accuracy of the wind tunnel predictions.

Several limited comparisons of wind tunnel measurements with hot-wire or hot-film probes and full-scale data are given in the literature [1–4]. All these studies are concerned with high-rise buildings. The agreement ranges from moderate to quite good. Generally, agreement is best for the windiest locations. For situations with low buildings, very few comparisons have been made. The one available comparison shows fairly poor agreement between the wind tunnel measurements and the full-scale situation [5]. Results of measurements with thermistor probes in the wind tunnel and full-scale values are given in [6,7]. Again, in both cases the situation near high-rise buildings was studied. The similarities are reasonable.

However, in the Netherlands wind comfort studies are not only carried out for high-rise buildings. Complaints at existing buildings show that wind discomfort (not danger) may occur for building heights starting from about 25 m. In addition, pedestrians require a better wind climate in shopping centres than around office buildings. This means that for shopping centres the threshold for discomfort can already be exceeded at relatively low building heights. Therefore, the building to be selected for the comparison test, had to cover preferably the whole range of possible situations, to be tested in a wind tunnel.

Street level wind climate validations are very scarce in the literature. Sanada et al. [7] report a comparison of wind climates. The agreement is dependent on the location, but is generally encouraging. The probability of a certain wind velocity being exceeded in comparison with wind discomfort criteria is decisive for the assessment of the wind climate. It determines whether an area can be used as designed by the architect or wind protective measures need to be taken.

In view of the importance of this item, extensive attention was also paid to the accuracy of the prediction of the wind climate.

2. The sites

The wind velocities around isolated high-rise buildings are determined by the wind velocities at roof height [8]. Generally speaking, this is also valid for a high-rise building in an urban environment of lower buildings [9]. Both the wind velocities in the wind tunnel and the wind velocities in the full-scale situation are mainly determined by the high-rise building. When the approaching wind profile and the surrounding buildings and obstacles are roughly modelled in the wind tunnel, this situation can be simulated relatively easily.

The situation becomes more complicated when the building does not rise above or does not rise much above the surrounding buildings or is even lower. The local wind velocities are then not only determined by the building itself, but also by the immediate surrounding buildings. In addition, the correct simulation of the approaching undisturbed wind velocity profile and the lay-out of the immediate surroundings (arrangement of surrounding buildings, the presence of trees, wooded areas, etc.)

becomes more important. This makes both better simulation of the approaching wind and representative seasonal simulation of the effect of trees and wooded areas necessary throughout the year. It will be clear that wind comfort predictions for low buildings in a wooded environment make greater demands on the execution of wind tunnel tests.

A conscious decision was taken in favour of comparison of one of the most difficult situations, namely a relatively low complex building in an environment surrounded by trees and wooded areas.

2.1. Complex low building

The TNO Laboratories in Apeldoorn satisfied these conditions. It is a relatively low (maximum height 16 m) complex building, with several variations in height, surrounded by trees and wooded areas in a wooded environment (Fig. 1). Fig. 2 shows the lay-out of the building and the estimated heights of the surrounding vegetation.

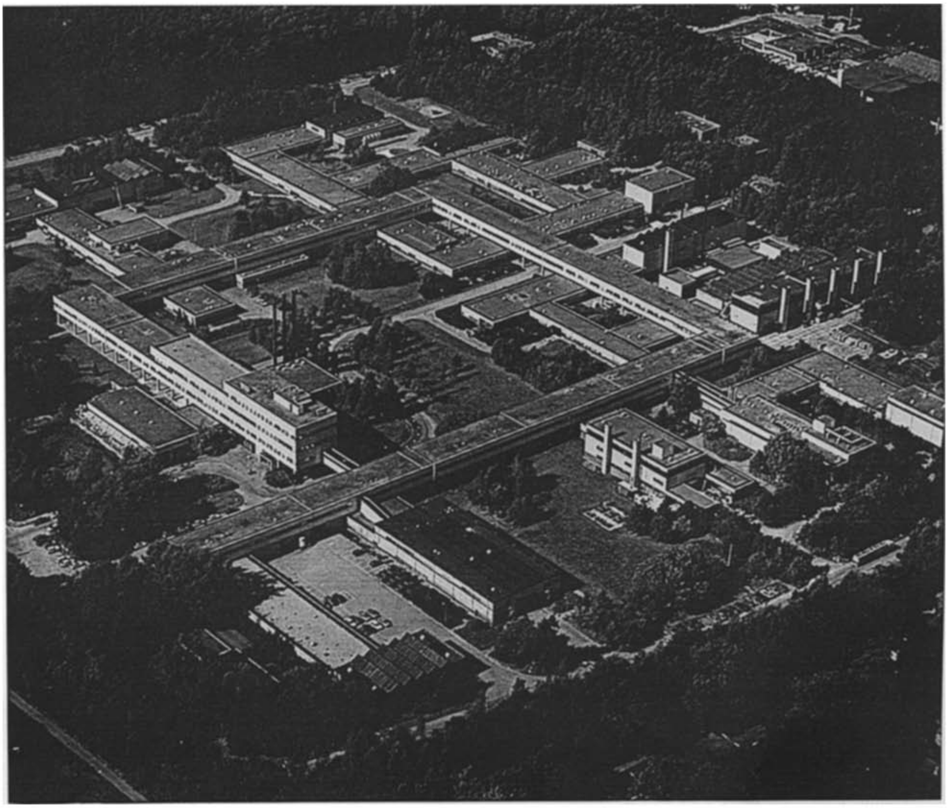

Fig. 1. TNO Laboratories Apeldoorn: a relatively low complex building surrounded by wooded areas and trees.

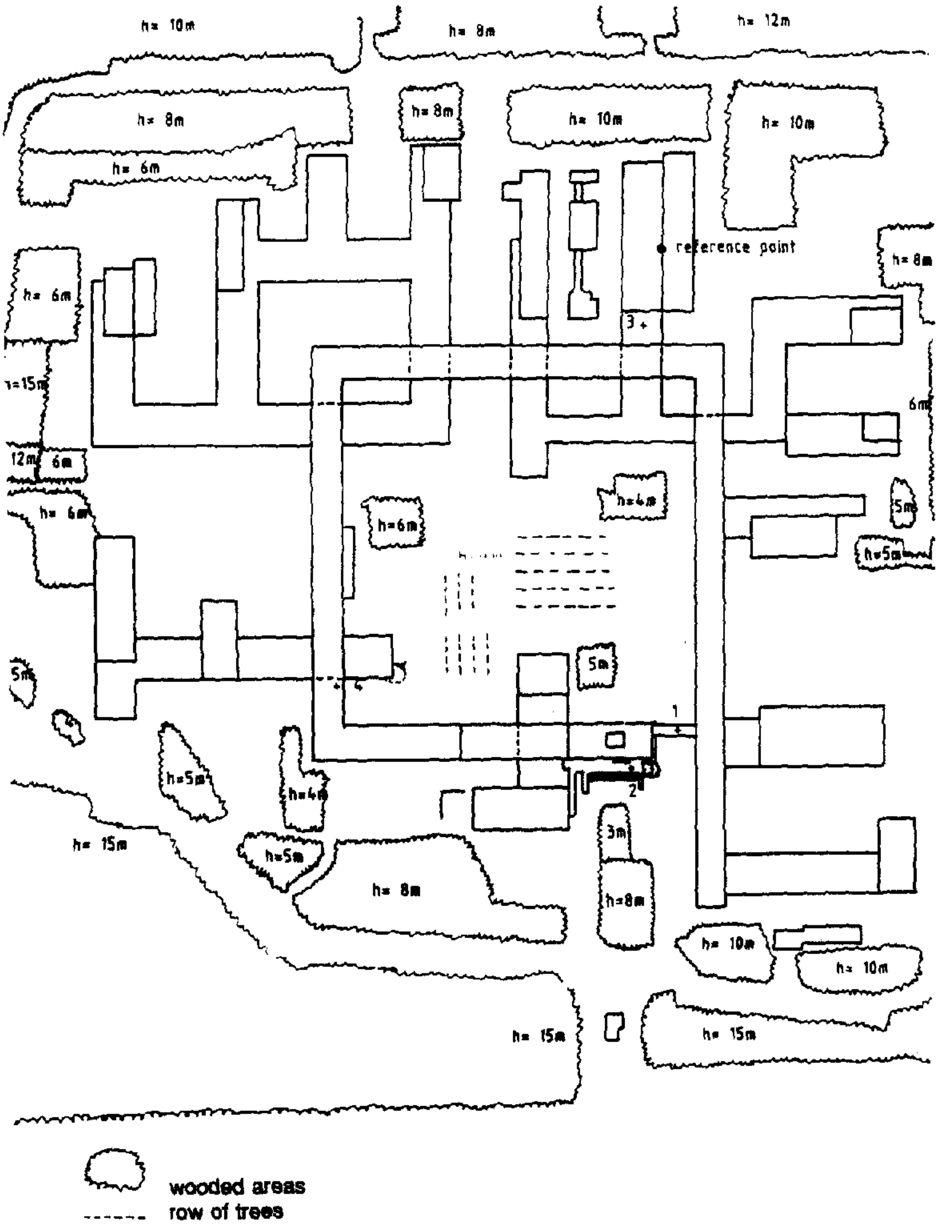

Fig. 2. Lay-out of the TNO Laboratories with measuring locations and estimated extents and heights of the wooded areas and trees. The top of the figure corresponds to the North.

The wind climate was first determined for 36 measuring points in the wind tunnel. From this, 4 locations with a different degree of wind discomfort and influenced differently by the building and the surrounding vegetation were selected for the full-scale measurements. The measuring positions are shown in Fig. 2.

The full-scale measurements were carried out in the period 1986–1987. Information on the effects of the seasons was also gathered in this way, especially in the summer (half May–half November) and winter (half November–half May) half years, whether the trees have leaves or not.

2.2. High-rise building

If, in the case of a complex low building, sufficient similarity is achieved between wind tunnel measurements and full-scale measurements it may be expected that other more simple situations can also be simulated successfully in the wind tunnel. This statement was checked by comparing the results of full-scale measurements at the base of a high rise building under construction with wind tunnel measurements. The purpose of the study was to determine in reality the wind climate at the entrance of a nearby office affected by a 75 m high tower building during the construction. A comparison between full-scale measurements and the wind tunnel study could be made because in an earlier stage a wind tunnel study had been carried out.

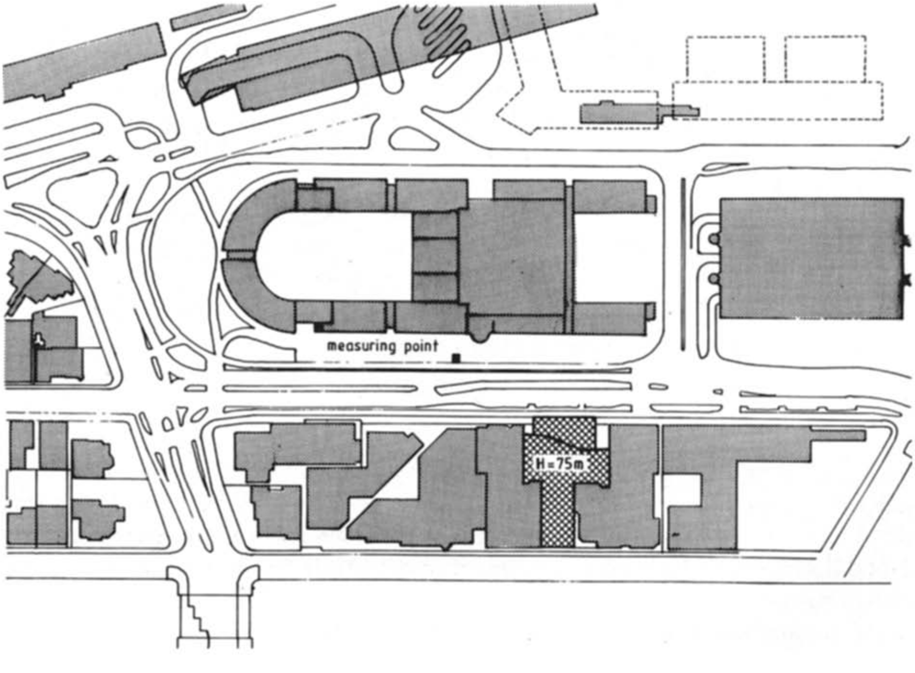

Fig. 3. High-rise building with measuring location.

The tower building has been built in a province town and is surrounded by relatively low buildings. Fig. 3 shows the site. The full-scale measurements were carried out at one location at the base of the tall building during a one-year period (1990).

3. Wind tunnel tests

3.1. Measurements

The wind tunnel measurements were carried out in the closed-circuit wind tunnel of the Department of Fluid Dynamics of IMET-TNO in Apeldoorn. The test section of this tunnel has a length of 5.4 m with a cross-section of 2.6×1.2 m^2. In front of the test section there is a foreland 8 m in length. Vorticity generators and a castellated barrier, combined with the surface roughness of the foreland, were used at the entrance to the test section in order to simulate the atmospheric boundary-layer. Five different atmospheric boundary-layers between marine and urban can be simulated by choosing the surface roughness. The wind tunnel and the atmospheric boundary-layer simulations are described by Builtjes and Vermeulen [10].

Both wind tunnel studies were carried out at a scale of 1:250. The wind velocities were measured at a height of 1.75 m full-scale with thermistor anemometers. Due to the relatively high time constant, these probes are not suitable for measuring fluctuating wind velocities. The effective averaging time corresponds to 10 min average values in the atmosphere [11]. In addition, at the low building complex the reference wind velocities and wind directions were measured with a hot-wire anemometer at a height of 16 m, 3.5 m above a local building wing (Fig. 2).

The effect of different surface roughnesses of the foreland (z_{0f}) on the wind velocities was studied for the complex low building situation. The roughness length ranged from the full-scale values $z_{0f} = 0.09$ m to $z_{0f} = 1.25$ m. The real roughness of the surroundings in the full-scale situation was estimated at about 1 m. The wooded areas were simulated with cages of gauze with a permeability of 57%. The rows of trees were simulated with zigzag folded pieces of gauze on stalks. The measurements were carried out with and without vegetation. The high-rise building situation was measured with a roughness length of the foreland of $z_{0f} = 0.625$ m. The wind velocity measurements were carried out for 24 wind directions in steps of 15°.

3.2. Wind climate prediction

In order to be able to predict the probability of certain wind velocity limits being exceeded, the measured wind velocities in the wind tunnel are combined with statistical wind velocity data from the nearest meteorological station, according to the method described by Vermeulen and Hooftman [12]. In this approach two steps can be distinguished:

(1) Coupling the wind tunnel with the full-scale site.

In this step the reference height is chosen above both the full-scale site and the wind tunnel model. It has become apparent from many studies that the wind velocities at pedestrian level around high-rise buildings are determined by the velocity at roof height of the building under consideration and the adjacent surrounding buildings (e.g. [8,9]). This makes the wind velocity at roof height upstream of the building under consideration a suitable reference wind velocity. For both the wind tunnel and the full-scale situation, the following equation holds:

$$C = \frac{U}{U_{z(\mathrm{ref})}}, \tag{1}$$

where U is the local wind velocity at a height of 1.75 m and $U_{z(\mathrm{ref})}$ the reference wind velocity (at roof height in the approaching flow).

(2) Coupling the full-scale site with the meteorological station.

In this step the relation is calculated between the reference wind velocity above the full-scale site and the wind velocity at the meteorological station, $U(10)_\mathrm{m}$, with:

$$\frac{U_{z(\mathrm{ref})}}{U(10)_\mathrm{m}} = C_\mathrm{m} C_0 \, . \tag{2}$$

The coefficient C_m represents the coupling between the full-scale situation and the meteorological station. C_0 is a correction to C_m due to the presence of roughness changes.

From the logarithmic wind velocity profiles above the full-scale site and the meteorological station, the ratios of the shear stresses and assuming a constant boundary-layer thickness of 500 m, the following equation for C_m can be derived [12]:

$$C_\mathrm{m} = \frac{\ln(z_\mathrm{ref}/z_{0\mathrm{s}})}{\ln(10/z_{0\mathrm{m}})} \left[\frac{25 + (\ln 500/z_{0\mathrm{m}})^2}{25 + (\ln 500/z_{0\mathrm{s}})^2} \right]^{\frac{1}{2}}, \tag{3}$$

where $z_{0\mathrm{m}}$ and $z_{0\mathrm{s}}$ are the roughness lengths at the meteorological station and at the site respectively (Fig. 4). This equation is valid for situations where the local wind velocity profile is in equilibrium with the local roughness. Generally this will not be

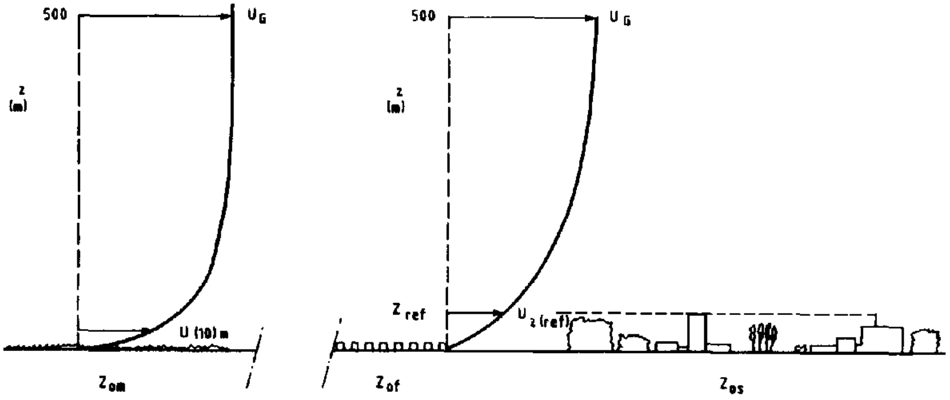

Fig. 4. Definition of the different roughness lengths.

the case. This means that the reference wind velocity calculated with Eq. (3) must be corrected for upstream roughness changes.

The growth of the internal boundary-layer is described in [12] by $d_i = 0.1\ x$. This means that the internal boundary-layer reaches the boundary-layer thickness of 500 m at $x = 5000$ m. On this basis for the correction factor C_0 the following equation can be derived:

$$C_0 = \left(\frac{x}{5000}\right)^{a1 - a2}, \tag{4}$$

where $a1$ and $a2$ are the exponents of the wind velocity profiles, respectively, upwind and downwind of the roughness change. In this case an exponential description of the velocity profiles is chosen because, in contrast to the logarithmic velocity profiles, this description can be used over the whole boundary-layer thickness.

The roughness changes between the location and the upstream distance of 5000 m are taken into account for every wind direction.

Combining Eqs. (1) and (2) gives:

$$C_u = \frac{U}{U(10)_\mathrm{m}}. \tag{5}$$

The probability of a certain wind velocity being exceeded at pedestrian level (U) can be expressed using the analytical Weibull function. As wind statistics are wind-direction dependent, the probability of exceeding for a certain wind sector can be written as:

$$F(>U) = \sum_{j=1}^{j=24} a_j \exp\left[-\left(\frac{U}{C_{uj} v_j}\right)^{k_j}\right], \tag{6}$$

where a_j is the part of the time the wind is blowing from the direction within the wind sector j, v_j and k_j are the Weibull parameters for the wind sector j and C_{uj} is the wind velocity coefficient for the wind sector j.

Estimating the roughness length of the site ($z_{0\mathrm{s}}$) is often difficult. The most realistic estimate of the roughness length for the complex low building situation is about 0.5 m. However, to gain some insight into the sensitivity for the roughness length of the site, calculations were also carried out for a roughness length of $z_{0\mathrm{s}} = 1$ m.

In wind comfort studies we are only interested in wind nuisance. In the literature, thresholds for wind nuisance or discomfort are given either in terms of mean wind velocities, equivalent wind velocities or gust velocities [8, 13–15]. Converted to mean wind speeds all values are between 3 and 6 m/s. In addition, Jackson [16] concluded from a questionnaire survey that a mean wind speed of 4 m/s was perceived as uncomfortable by about 50% of people.

It can, thus, be concluded that a mean wind speed at pedestrian level of 5 m/s can be considered a reasonable value for the onset of discomfort. It corresponds to Beaufort 4. In most wind comfort studies of IMET-TNO the probability of the 5 m/s wind velocity being exceeded is therefore calculated. However, the value selected is not really important for the comparison.

These standard data are converted to the number of hours or days with discomfort by multiplying the probability of exceeding by the number of hours or days in a year.

4. Full-scale measurements

4.1. Measurements

The measurements at the low building complex were carried out using a mobile Thiess three-cup anemometer with a wind vane. The measuring height was the same as in the wind tunnel measurements (1.75 m). The wind velocities at the four locations were measured successively. The measuring period ranged from 5 to 7 months per location. The variations of wind direction and wind velocity in the wind tunnel only include fluctuations at time scales smaller than about 10 min in full-scale. Therefore, time averaged wind tunnel measurements can be considered to be representative for 10 min average values in full-scale. The reference wind velocities and wind directions were measured with a fixed cup anemometer with a wind vane at a height of 16 m, 3.5 m above the local building wing (Fig. 2).

At the high-rise building location an EKO10 data-logger was used in conjunction with a cup anemometer and a wind vane. Every hour during the measuring period the mean wind speed, the mean wind direction and the maximum wind speed during the hour (1 s value) was recorded.

4.2. Wind climate determination

The full-scale measurements did not last long enough for long-term local wind statistics to be obtained. The wind climate was, therefore, determined from the full-scale measurements by calculation. For each location at the low building complex, the ratios (C) of the local wind velocity and the wind velocity at the reference height were determined for the similar time series, divided into day and night, summer half year and winter half year. Ratios at low reference wind velocities may be unreliable because of thermal stability effects of the atmosphere, effects of the start-up velocities of the cup anemometers, etc. These ratios were, therefore, calculated for every location and for every wind direction, and plotted against the reference wind velocity. Fig. 5 shows an example of location 3 for all wind directions. The general tendency of these plots shows large C values and large standard deviations for low reference wind velocities. As the reference wind velocities increase, the C values decrease until they become more or less constant at reference wind velocities between 2 and 4 m/s. The analyses were, therefore, restricted to data with reference wind velocities higher than 4 m/s. These data were combined with the corresponding wind data of the nearest meteorological station (Deelen; at a distance of about 15 km), taking into account summer and winter time.

Using regression analyses, the relations (C_u) between the local wind velocity U and the simultaneously occurring wind velocity at the meteorological station $U(10)$ were determined for every wind direction, divided into a summer and a winter half year.

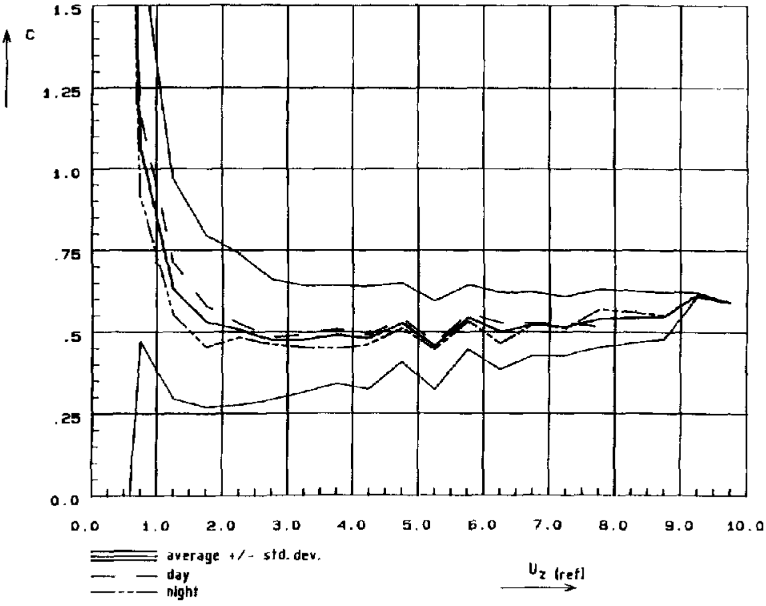

Fig. 5. Variation of the wind velocity coefficients for location 3 with the reference wind velocity (wind directions 0°–345°).

Afterwards, for the summer and winter half year the probability of the wind velocity threshold value for discomfort of 5 m/s being exceeded was calculated with Eq. (6) for every wind direction (in steps of 15°) with available data. Addition gave the total number of hours the 5 m/s limit is exceeded.

5. Validation method

The wind velocity coefficients C_u are used in conjunction with the wind statistics of the nearest meteorological station to estimate the wind climate. They are calculated in two steps:

$$C_u = \frac{U}{U_{z(\text{ref})}} \frac{U_{z(\text{ref})}}{U(10)_{\text{m}}} = \frac{U}{U(10)_{\text{m}}}.$$

For the validation of wind tunnel measurements, the first term is decisive. This step determines the reliability of the wind tunnel measurements. The second term describes the coupling of the reference wind velocity with the wind velocity at a height of 10 m at the nearest meteorological station. This step is necessary for the prediction of the wind climate and can be considered as a second validation step. In this step additional variables such as the method of coupling wind tunnel measurements to meteorological data and the effects of roughness changes arise. These variables do not affect the reliability of the wind tunnel measurements, but obviously do determine the accuracy of the prediction of the wind climate. An ultimate validation of this step is rather complex and far beyond the scope of the present study.

Although we have compared the wind climates calculated from the wind tunnel measurements with the wind climates calculated from the full-scale measurements, it cannot be seen as a complete validation of step 2. However, it obviously gives a good indication of the accuracy of the prediction of the wind climate.

For the full-scale measurements, the probabilities of the 5 m/s limit being exceeded were calculated for the wind directions for which sufficient data were available. For the same wind directions, the probabilities of exceeding were calculated for the wind tunnel measurements.

6. Results

6.1. *Wind velocity coefficients*

For the complex low building, the ratios (C) of local wind velocities at a height of 1.75 m and reference wind velocities of wind tunnel measurements and full-scale measurements have been compared. The similarities are best with a roughness length of the foreland of $z_{0f} = 1.25$ m (Fig. 4). This roughness length agrees best with the estimated roughness of the immediate environment of the building, consisting of woods and trees. This means that for relatively low buildings the roughness of the approaching flow must be simulated as well as possible. A greater margin exists for high-rise buildings.

Fig. 6 gives as an example the C values as a function of the wind direction for location 1. It shows that in most cases the results of the wind tunnel measurements are within the standard deviation of the full-scale measurements. Both the variation of the coefficient with the wind direction and the absolute values are predicted well.

Fig. 7 gives the average C values for the same location, but this time split into data for the summer and winter half years. The summer data are lower than the winter data, showing the wind protective effect of the wooded areas and the trees.

For all four locations the C values of wind tunnel measurements and full-scale measurements are compared in Fig. 8, again split into data for the winter and the summer half years. The winter data (Fig. 8a) show good agreement, whilst for the summer data the scatter is greater (Fig. 8b). This is not surprising. The wooded areas and rows of trees, pine trees and foliage trees are mixed in different arrangements, resulting in different permeabilities. Because it is very hard to estimate both the heights and the permeabilities of the different parts of the wooded areas in summer and winter, all wooded areas and rows of trees were simulated with gauze with one permeability (57%). It was estimated from the wind protection of green-belts in summer and winter that this simulation must give an average vegetation of pine and foliage trees for both the summer and the winter half years. The heights were roughly estimated, but deviations of a few metres cannot be ruled out. It is evident that if wind tunnel measurements agree well with the winter half year, the summer half year will generally give an overestimate of the local wind velocities,

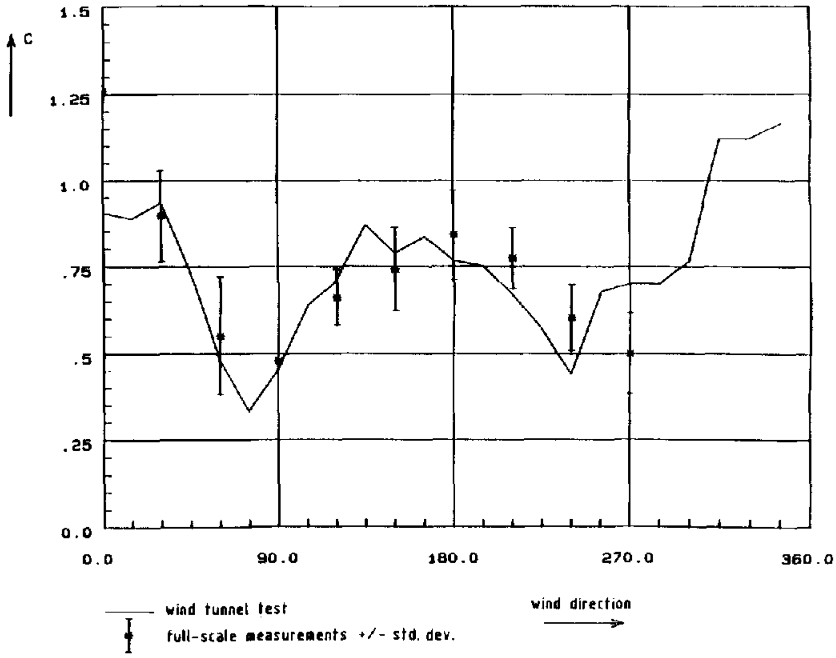

Fig. 6. Complex low building: comparison of wind tunnel test with full-scale data for measuring location 1.

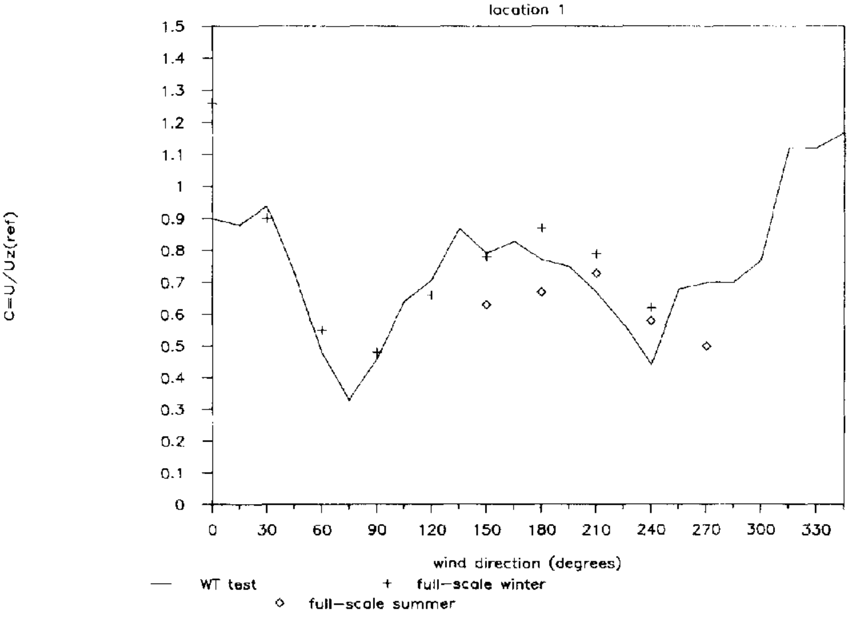

Fig. 7. Complex low building: comparison subdivided into data for the summer and the winter half years

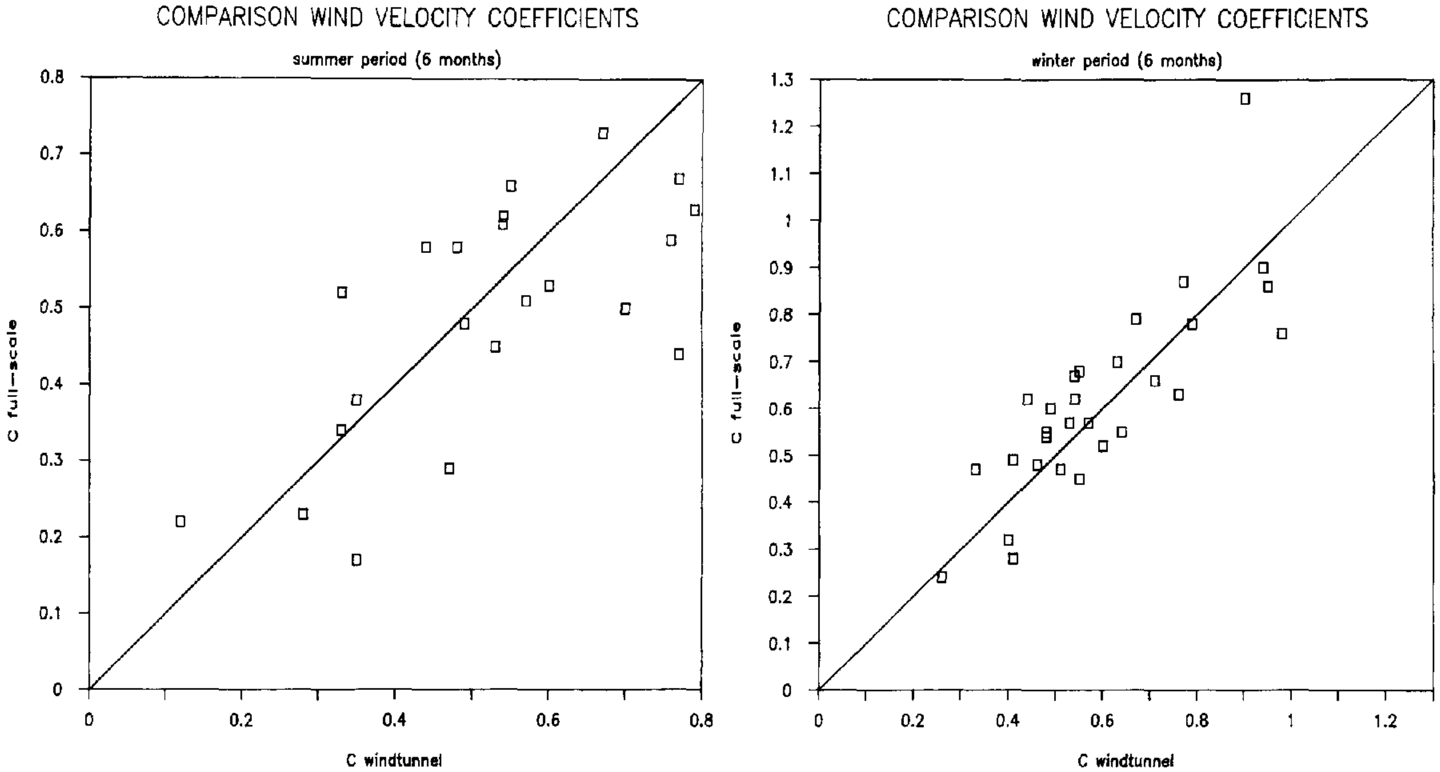

Fig. 8. Complex low building: comparison between wind tunnel test and full-scale data for all locations: (a) winter half year, and (b) summer half year.

Table 1
Correlations between wind tunnel measurements ($_{\mathrm{WT}}$) and full-scale measurements ($_{\mathrm{fs}}$); for $z_{0\mathrm{f}} = 1.25$ m

Loc.	Winter half year	Summer half year
1	$C_{\mathrm{fs}} = 0.02 + 1.09\ C_{\mathrm{WT}} (r = 0.93)$	$C_{\mathrm{fs}} = 0.07 + 0.79\ C_{\mathrm{WT}} (r = 0.90)$
2	$C_{\mathrm{fs}} = 0.001 + 1.17\ C_{\mathrm{WT}} (r = 0.99)$	$C_{\mathrm{fs}} = -0.05 + 1.05\ C_{\mathrm{WT}} (r = 0.88)$
3	$C_{\mathrm{fs}} = -0.03 + 1.07\ C_{\mathrm{WT}} (r = 0.92)$	$C_{\mathrm{fs}} = 0.01 + 1.04\ C_{\mathrm{WT}} (r = 0.97)$
4	$C_{\mathrm{fs}} = 0.08 + 0.76\ C_{\mathrm{WT}} (r = 0.96)$	$C_{\mathrm{fs}} = 0.12 + 0.59\ C_{\mathrm{WT}} (r = 0.84)$
All four locations together:	$C_{\mathrm{fs}} = 0.06 + 0.93\ C_{\mathrm{WT}} (r = 0.87)$	$C_{\mathrm{fs}} = 0.12 + 0.70\ C_{\mathrm{WT}} (r = 0.78)$

because the leaves increase the resistance to wind in comparison with the leafless winter period.

The correlations between wind tunnel measurements and full-scale measurements for all four locations are given in Table 1, again split into winter and summer half years.

The correlation coefficients (r) for the winter half year range between 0.92 and 0.99 and for the summer half year between 0.84 and 0.97. Except for location 3, the correlations for the winter half year are greater than for the summer half year. The lowest correlation coefficient for the summer half year is found at location 4. Fig. 2 shows that this is a location under a building wing with vegetation beside it in the direction of the prevailing wind (South/West). It is stated above that height and permeability of the vegetation is not known and can only be roughly estimated. Particularly close to vegetation, deviations from the full-scale situation can cause considerable difference in wind velocities. Analyses of the data show that for location 4 only the value 1 is not within the 95% confidence interval of the slope of the regression line, showing a systematic deviation. Obviously, for location 4 the wind tunnel simulation has not been similar enough to the full-scale situation for the summer half year.

From a physical point of view the regression lines had to pass through the origin. Analysis of the data show that for all four locations the origin is within the 95% confidence interval of the intercept.

The results in Table 1 suggest that the simulation of the vegetation with gauze with a permeability of 57% agrees best with a winter situation.

6.2. *Wind climate*

6.2.1. *Complex low building*

From the wind velocity coefficients for the winter and summer half year the yearly averaged wind climates were calculated. Fig. 9 presents a comparison of the calculated wind climates based on a roughness length of the foreland of $z_{0\mathrm{f}} = 1.25$ m and a roughness length of the location of $z_{0\mathrm{s}} = 0.5$ m. It shows that the relative wind climates with respect to each other are predicted well by the wind tunnel test. In

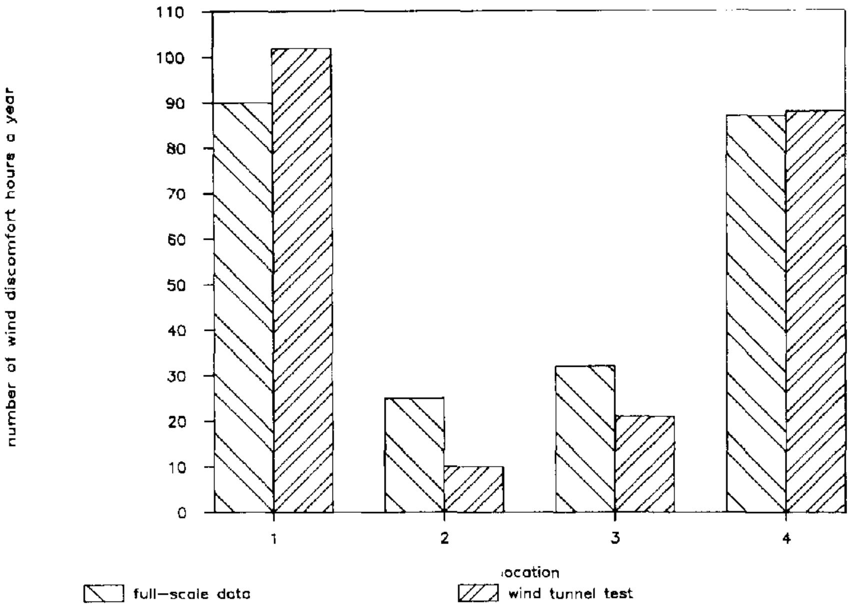

Fig. 9. Complex low building: predicted yearly averaged wind climates from the wind tunnel test compared with the full-scale situation.

addition, the absolute values for locations 1 and 4 are predicted well. The agreement for location 3 is reasonable and for location 2 moderate. It appears that the deviations from the full-scale values are caused by relatively small underestimates of some wind velocity coefficients (C_u) in the southwesterly wind sector. This is the prevailing wind sector in the Netherlands, which makes the major contribution to wind discomfort. Relatively small differences in C_u values in this wind sector result in large differences in the number of hours with discomfort. In the wind sector 255° (247.5° – 262.5°), for instance, a C_u value of 0.41 gives $2\frac{1}{2}$ times more hours with wind discomfort than a slightly lower value of 0.37. This means that the accuracy of the wind comfort prediction is strongly determined by the accuracy of the wind velocity coefficients in the prevailing wind sector.

However, it can generally be concluded that despite the complex situation of low buildings and much vegetation there is a reasonable to good agreement between wind tunnel tests and full-scale measurements. This also means that the simulation of the wooded areas with pieces of gauze gives a sufficient reliable approximation of the yearly averaged situation.

Without a simulation of the vegetation, the number of hours with discomfort are greatly overestimated. This means that it is necessary to simulate vegetation in wind tunnel studies, at least for situations where the height of the vegetation is roughly of the same order as the height of the buildings.

For a roughness length of the foreland of $z_{0f} = 0.625$ m instead of $z_{0f} = 1.25$ m the agreement between wind tunnel tests and full-scale measurements only changes slightly. However, a good estimate of the roughness length of the site appears to be very important (Fig. 4). The most realistic value of $z_{0s} = 0.5$ m gives the best agreement with the full-scale data. An overestimate of the local roughness length by a factor 2 in this situation produces a dramatic decrease (by a few factors) in the number of hours with wind discomfort. This shows the importance of an accurate estimate of the local roughness of the site.

6.2.2. *High-rise building*

The wind climate at the entrance of a neighbouring office of the high-rise building was determined during different phases of its construction.

In a wind tunnel study both the situation with and without the high-rise building was tested, enabling the comparison of the two situations.

Fig. 10 shows that wind tunnel and the full-scale measurements agree within 5 days. As expected, the number of discomfort days per year increases with increasing building height.

Fig. 11 compares the number of discomfort days per year as a function of the wind direction for the situation without and with the high-rise building. The southwesterly wind direction, which is highly prevalent in the Netherlands, obviously makes the greatest contribution to the number of discomfort days. The agreement between wind tunnel measurements and full-scale measurements is very good, not only for the high-rise building but also for the situation without high-rise building.

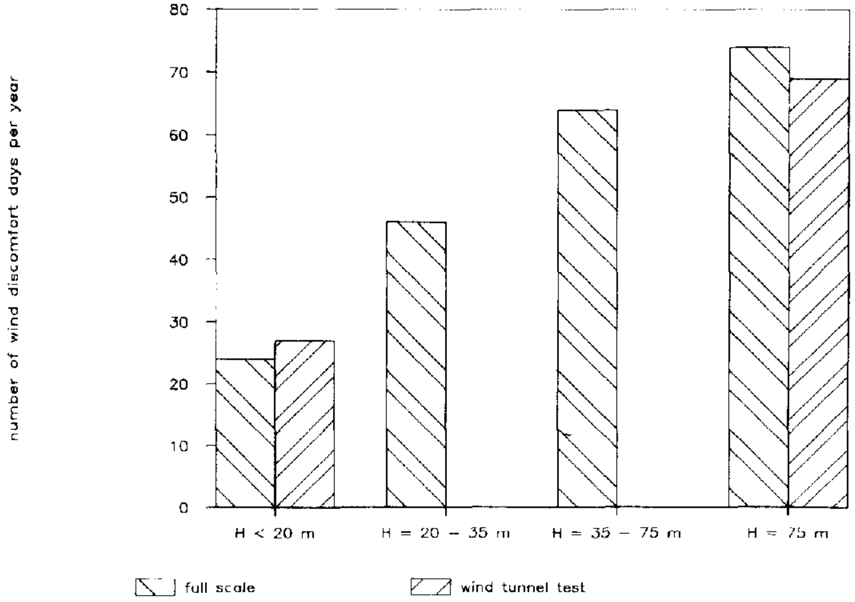

Fig. 10. High-rise building under construction: comparison with wind tunnel experiments.

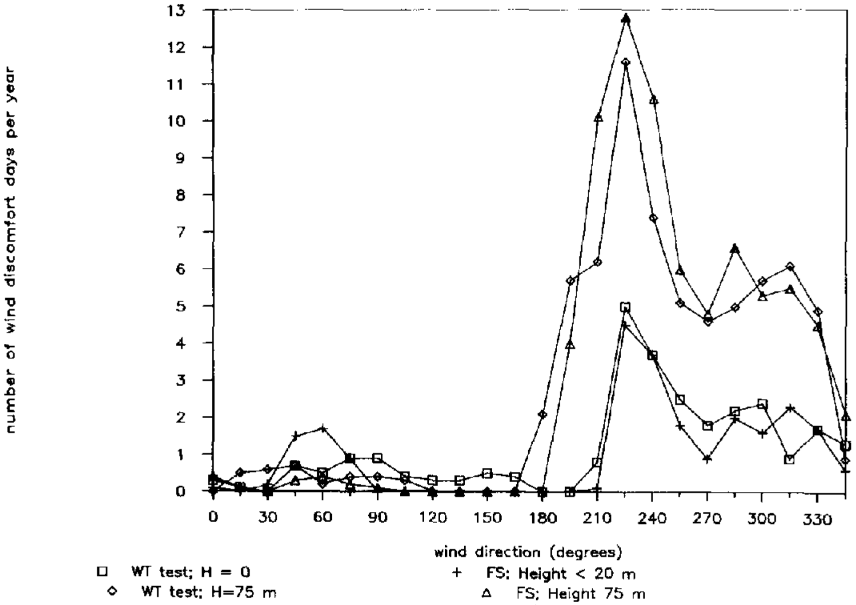

Fig. 11. High-rise building: comparison of full-scale measurements with wind tunnel measurements, without (< 20 m) and with completed high-rise building, as a function of the wind direction.

7. Conclusions

With the correct roughness length of the foreland, the wind tunnel tests give a good prediction of the ratios between the local wind velocities at pedestrian height and the wind velocities at a reference height, with respect to both the relative changes with the wind direction and the absolute values. This is even the case for a complex low building in a complex wooded environment.

The wooded areas around a low building complex were simulated with pieces of gauze with 57% permeability. This produces good correlation with the full-scale measurements for the winter half year, with correlation coefficients between 0.92 and 0.99. For the summer half year the correlation coefficients are lower: between 0.84 and 0.97.

However, the pieces of gauze give a sufficiently reliable approximation of the yearly averaged wind climate.

The method used at TNO to predict the wind climate around buildings is a combination of wind tunnel measurements with simple omnidirectional wind velocity sensors and the coupling of these data to a representative meteorological station, taking into account the wind direction dependent upstream roughness changes.

For the Dutch situation the accuracy of the wind comfort prediction is mainly determined by the accuracy of the wind velocity coefficients in the prevailing southwesterly wind sector. Relatively small differences in wind velocity coefficients in this wind sector can result in considerable deviations in the wind discomfort prediction. Nevertheless, from the two cases it can be concluded that the method generally gives a good agreement with the wind climate for the full-scale situation, both for a low complex building in a wooded environment and for a high-rise building in an urban environment with relatively low buildings. However, a good estimate of the local roughness length of the site is necessary for a reliable prediction of the local wind climate. In addition, vegetation cannot be neglected in a wind tunnel simulation, especially in situations with relatively low buildings.

References

[1] N. Isyumov and A.G. Davenport, Comparison of full-scale and wind tunnel wind speed measurements in the commerce court plaza, J. Ind. Aerodyn., 1 (1975) 201–212.

[2] R.C.F. Dye, Comparison of full-scale and wind-tunnel model measurements of ground winds around a tower building, J. Wind Eng. Ind. Aerodyn., 6 (1980) 311–326.

[3] J. Gandemer, Simulation and measurement of the local wind environment, Proc. Workshop Wind Tunnel Modelling for Civil Engineering Applications, Gaithersburg, USA, April 1982.

[4] S. Kawamura, E. Kimoto, T. Fukushima and Y. Tanike, Environmental wind characteristics around the base of a tall building – A comparison between model test and full-scale experiment, J. Wind Eng. Ind. Aerodyn., 28 (1988) 149–158.

[5] G.I. Fekete, Wind speed measurements on the walk-ways of Habitat 67, Symp. Designing with the wind,Nantes, June 15–19, 1981.

[6] S. Murakami, K. Uehara and H. Komine, Amplification of wind speed at ground level due to construction of high-rise buildings in urban area, J. Ind. Aerodyn., 4 (1979) 343–370.

[7] S. Sanada, Y. Iwasa and Yoshida, Full-scale measurements of environmental wind in the Shinjuku new metropolitan centre, J. Wind Eng. Ind. Aerodyn., 6 (1980) 291–309.

[8] A.D. Penwarden and A.F.E. Wise, Wind environment around buildings, BRE report B 75–49, 1975.

[9] J.A. Leene, Building wake effects in complex situations, 8th Int. Conf. on Wind Engineering, London, Canada, July 12–15, 1991.

[10] P.J.H. Builtjes and P.E.J. Vermeulen, Atmospheric boundary layer simulation in the "PIA" and "MIA" windtunnels of TNO-Apeldoorn, MT-TNO Report 80-0290, 1980.

[11] P.E.J. Vermeulen, Dynamic response of thermistor probes, MT-TNO note, November 1984 (in Dutch).

[12] P.E.J. Vermeulen and P. Hooftman, Method for the determination of the relation between the wind velocity at a meteorological station and the local wind velocities measured on a model in a wind tunnel, MT-TNO Report 80-02760, 1980, (in Dutch).

[13] J.C.R. Hunt, E.C. Poulton and J.C. Mumford, The effects of wind on people, new criteria based on wind tunnel experiments, Building and Environment, 11 (1976) 15–28.

[14] H. Cohen et al., Pedestrians and wind in the urban environment, Massach. Univ., Amherst, USA, 1977.

[15] S. Murakami, et al., Wind effects on people, 5th Int. Conf. on Wind Engineering, Fort Collins, CO, USA, 1979.

[16] P.S. Jackson, The evaluation of windy environments, Building and Environment, 13 (1978) 251–260.

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Accuracy of assessment of wind speed in the built environment

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Abstract

Wind tunnel simulations and criteria for wind comfort and safety are used to assess the wind climate in the built environment. Probability of occurrence of a critical wind speed is derived from as well wind tunnel results as data from a meteorological station. The paper discusses sources of error in the various steps. It is shown that at least a 20% standard deviation in the estimate of local wind speeds has to be accounted for. This error has impact on the application of various comfort criteria. © 2002 Published by Elsevier Science Ltd.

Keywords: Wind comfort; Comfort criteria; Comfort evaluation; Wind tunnel comparison

1. Introduction

In the Netherlands, a program has been initiated aiming at standardising the assessment of wind climate of building plans. Among its goals are standard criteria for wind comfort and rules for wind tunnel investigations, CFD calculations and for use of climatological data. The program incorporates literature surveys and experience during three decades of practice. The standard is meant as a document for a new development in the built environment. Since it is expected to become an important tool for local authorities it is necessary to determine the accuracy of the methods.

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2. Methodology

A wind speed ratio C_V is defined as being the ratio between the hourly mean wind speed V_{PED} at pedestrian height and the hourly mean wind speed V_{REF} at some location at reference height Z_{REF}.

For the so-called in situ (IS) situation this results in:

$$C_{V,IS} = \frac{V_{PED,IS}}{V_{REF,IS}}. \tag{1}$$

For the wind tunnel (WT) simulation:

$$C_{V,WT} = \frac{V_{PED,WT}}{V_{REF,WT}}. \tag{2}$$

In a perfect simulation the $C_{V,WT}$ is equal to the $C_{V,IS}$. The IS wind speed at pedestrian height $V_{PED,IS}$ can then be determined as follows:

$$V_{PED,IS} = C_{V,WT} V_{REF,IS}. \tag{3}$$

The $V_{REF,IS}$ is derived from the hourly mean wind speed V_{MET} at 10 m height at a nearby meteorological station by some transfer function T:

$$V_{REF,IS} = T V_{MET}. \tag{4}$$

Both $C_{V,WT}$ and T are loaded with errors of various kinds. Assuming random errors with standard deviations of δC_V and δT the following relation may be framed:

$$V_{PED,IS} = (C_{V,WT} \pm \delta C_V)(T \pm \delta T) V_{MET}. \tag{5}$$

The δC_V is dependent on the quality of the wind tunnel simulation and will be discussed in Section 3. The δT is dependent on the quality of the applied model to correlate wind data from a meteorological geographic location with the basic wind climate at the geographic location of the building site. This will be discussed in Section 4.

The effects from δC_V and δT on the accuracy of the calculated wind speed at pedestrian height will be discussed in Section 5. In Section 6, the consequences for the assessment of the wind climate will be discussed.

More than 25 years ago it was already recognised that thermal comfort and the cooling effects from wind should be considered in the assessment of wind comfort. Recent work [1–3] renewed this attention to thermal effects. The present paper however is based on present day practice in The Netherlands, whereby thermal effects are not considered.

3. Accuracy of the wind speed ratio

In literature an effective wind speed V_{EFF} is defined, in which the effects of wind gusts on wind discomfort and danger are accounted for. The definition of an effective wind speed V_{EFF} in non-dimensional form is

$$C_{\text{V,EFF}} = C_{\text{V}}(1 + kI_{\text{U}}), \tag{6}$$

where I_{U} is the longitudinal turbulence intensity and k has a value varying in literature from 0 to 3.5. With a typical value of $I_{\text{U}} = 0.20$ (i.e. 20%), the difference between applying $k = 0$ and 3.5 results in a 70% difference in the $C_{\text{V,EFF}}$ value. This affects of course greatly the further results of the assessment.

Wind tunnel test data may incorporate turbulence characteristics directly (the rms-value of the time signal of the wind speed sensor is measured) or indirectly (the time-mean value of the sensor output will be higher as a result of turbulence). This means that a proper choice of k should depend on the applied sensor in the wind tunnel. The heated thermistors as used in the Netherlands are expected to respond mainly on the mean wind speed and a high k-value should then be used to define V_{EFF}. The matter of an effective wind speed ratio and the corresponding error due to turbulence is left out of discussion here.

The standard error δC_{V}, defined in Eq. (5), is caused by technical and simulation errors:

- the atmospheric boundary layer (ABL) in the wind tunnel differs from IS,
- the model differs from details in the urban geometry and in the surrounding area,
- wind tunnel characteristics as short and long term change of the flow with time which cannot be accounted for,
- drift of sensor accuracy and sensor sensitivity; response of sensors to highly turbulent flow conditions, which vary with wind speed and flow angle,
- inappropriate choice of the reference height Z_{REF}.

To study random errors comparative tests were performed at three different wind tunnels in the Netherlands. An imaginary built environment was modelled on scale 1:250. The same physical model was used by all three parties and tested under simulated ABL conditions. The targeted ABL profile had a value of 0.03 m for the roughness parameter z_0.

In the model 52 measuring stations were defined. At these positions the wind speeds were measured at 24 wind directions β (step size 15°) and reduced to wind speed ratios $C_{\text{V,WT}}$. Each wind tunnel thus provided 1248 $C_{\text{V,WT}}(\beta)$ values to be compared.

The results from one wind tunnel showed a systematic deviation compared to the other two wind tunnels. This will not be discussed further, as a systematic error might in principle be solved.

For the present discussion the random errors are of interest. Fig. 1 gives a presentation of the test results from wind tunnels "*a*" and "*b*".

The ratios between the $C_{\text{V,WT}}$-values as measured at wind tunnel "*a*" and wind tunnel "*b*" at similar wind directions are plotted along the vertical axis and the C_{V}-values from wind tunnel "*a*" along the horizontal axis. Ideally, the $C_{\text{V,WT}}$ ratios plotted on the vertical scale should all be equal to unity. The results show however a scatter with a bandwidth of approximately 50%; a corresponding standard deviation

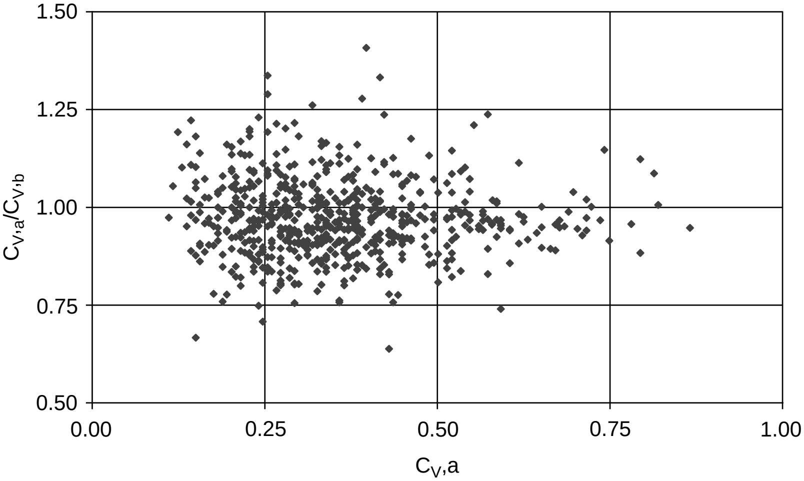

Fig. 1. Results of comparative tests between wind tunnels *a* and *b*.

of 12% was calculated. A comparison of any two wind tunnels resulted in a similar conclusion.

The test only covers a part from the above-summarised technical and simulation errors. Although a building location is characterised by different upstream surface roughness at varying wind directions, routine wind simulations use one surface roughness for all wind directions. A description of the upstream roughness will easily be one class off in the roughness classification [4], with effects on wind speed and turbulence characteristics. If for example $z_0 = 1$ or 0.5 m and if the displacement length $d = 10$ m, the longitudinal turbulence intensity I_U at height $z = 50$ m is either 27% or 22%. The authors are not aware of any information regarding the magnitude of this error with regard to pedestrian level wind tests.

It is suggested [5] that the effect of stability may be compensated by climatologically averaging, but quantification is lacking. We think that the remaining errors will give an extra standard deviation in C_V of at least another 10%. Since these errors are independent, the total standard deviation then becomes 15%, i.e. $\delta C_V/C_V = 0.15$.

4. Accuracy of the reference wind

The ratio T as defined in Eq. (4) represents the transfer from the documented wind speed at a nearby meteorological station to the wind speed at the building plan area at the reference height Z_{REF}. An estimate of T is based on values for the surface roughness at varying wind direction and an internal boundary layer growth model in a neutral atmosphere. This estimate incorporates errors.

De Wit et al. [6] analysed wind measurements over Eindhoven. They found that the error in the calculated T-value had a standard deviation of about 9%. They also found at a reference height of 42 m a random variation in the wind speed with a standard deviation of 0.7 m/s. This is 14% of 5 m/s, a wind speed value often used as threshold in wind comfort studies.

An additional error in the source data of the meteorological wind speed V_{MET} of say 10% will affect the $V_{\mathrm{REF,IS}}$ for another 10%.

For the time being we estimate from these errors a standard error in T of 15%, i.e. $\delta T/T = 0.15$.

5. Accuracy of the pedestrian level wind speed

The estimates of $\delta C_{\mathrm{V}} = 15\%$ and $\delta T = 15\%$ mean that according to Eq. (5) the IS pedestrian level wind speed $V_{\mathrm{PED,IS}}$ can be estimated within a standard deviation of about 20%.

Isyumov [7] compared in a study at the campus of the University of Western Ontario the mean wind speed ratios $C_{\mathrm{V,IS}}$ as measured IS with wind tunnel ratios $C_{\mathrm{V,WT}}$. The $V_{\mathrm{REF,IS}}$ was estimated from V_{MET} and a reference anemometer at another location of the campus. We estimate that the data show a range for $C_{\mathrm{V,IS}}/C_{\mathrm{V,WT}}$ of 0.4–1.6, with at $C_{\mathrm{V}} = 0.5$ a standard error of about 20%. The small amount of data is in line with the present error estimate.

Visser and Cleijne [8] measured $V_{\mathrm{REF,IS}}$ for a low-rise location in wooded countryside in the Netherlands and estimated the upwind roughness lengths z_0. The authors studied four locations. At an optimal choice of z_0 they found values of $C_{\mathrm{V,IS}}/C_{\mathrm{V,WT}}$ of 0.8–1.2 in a winter half-year and of 0.6–1.0 in a summer half-year. For all four locations together they found $C_{\mathrm{V,IS}} = 0.06 + 0.93C_{\mathrm{V,WT}}$ (correlation coefficient $r = 0.87$) in winter and $C_{\mathrm{V,IS}} = 0.12 + 0.70C_{\mathrm{V,WT}}$ ($r = 0.78$) in summer. These data are also in line with the present error discussion.

Williams and Wardlaw [9] studied the wind regime in the city of Ottawa. The wind speed V_{LOC} at a 213 m high measuring point was found to be 1.226 times the V_{MET} value. They required 1250 h of data to get this ratio within 10% of the mean value and 2935 h to get it within 0.5%. This information indicates that the standard deviation of this ratio is surprisingly great. The correlation coefficient between $C_{\mathrm{V,IS}}$ (with V_{REF} being the gradient wind) and $C_{\mathrm{V,WT}}$ was only 0.7, indicating that the wind tunnel simulation could not explain half of the variance. However, the ratios of the pedestrian level winds and the wind speeds at the closest tower as determined IS and in the wind tunnel correlated very well. The study of Williams and Wardlaw illustrates very well the difficulty in the calculation of T in Eq. (4), even if the wind tunnel simulation is completed with IS measurements.

Murakami et al. [10] also compared IS wind speed ratios (with V_{REF} at 120 m height) with wind tunnel values. From their scatter diagram the present authors conclude to a standard error of 40% at $C_{\mathrm{V,IS}} = 0.2$ up to 10% at $C_{\mathrm{V,IS}} = 0.8$.

6. Assessment of wind comfort

To assess wind comfort at some location *i* it is needed to know the probability P_i that the local wind speed $V_{\mathrm{PED,IS}}$ exceeds a certain threshold value V_{THR}. The probability P_i is the sum of the probabilities at distinguished classes for the wind direction β.

$$P_i = \sum_n P_i\{V_{\mathrm{PED,IS}} > V_{\mathrm{THR}}; \beta\}, \tag{7}$$

where *n* being the number of wind direction classes in the wind tunnel simulation.

A code of wind comfort assessment provides values for V_{THR} and the maximum value P_{MAX} of P_i. Values of V_{THR} and P_{MAX} may depend on the planned use of the urban space under consideration.

A combination of Eqs. (5) and (7) yields

$$P_i = \sum_n P_i\{(C_{\mathrm{V,WT}} \pm \delta C_{\mathrm{V}})(T \pm \delta T)V_{\mathrm{MET}} > V_{\mathrm{THR}}\}. \tag{8}$$

The errors δC_{V} and δT are stochastic in nature and will therefore affect the P_i in a stochastic way. With SD being the standard deviation and P_{MEAN} the average value, one may write for location *i*:

$$P_i = P_{\mathrm{MEAN},i} \pm \mathrm{SD}_i. \tag{9}$$

Assuming a normal distribution for the error in P_i:

$$\mathrm{Probability}\{P_i < P_{\mathrm{MEAN},i} + 1.6\mathrm{SD}_i\} = 0.95. \tag{10}$$

The next step is to determine the magnitude of SD_i in order to get 95% confidence levels for calculated P_i values.

The regional climate and the geometry of the built environment determine how strongly the probability $P_i\{V_{\mathrm{PED,IS}} > V_{\mathrm{THR}}; \beta\}$ depends on the wind direction β. It is therefore not possible to estimate analytically the contribution of δC_{V} and δT to SD.

The authors calculated $p_{\mathrm{MEAN},i}$ and SD_i values from some post processing of an available wind tunnel test on a 19th century quarter with additional high rise buildings in one of the major cities in the Netherlands. Threshold wind speeds of 5 and 15 m/s were used for the assessment of, respectively, wind comfort and danger. At 76 measuring stations wind speed ratios $C_{\mathrm{V}}(\beta)$ were determined at 12 wind directions β. Each station thus had 12 $C_{\mathrm{V}}(\beta)$ values. A coupling with the wind climate data of Amsterdam airport (through the transfer function *T*) resulted for each station *i* in one probability value $P_i(\beta)$ for exceeding 5 m/s and one probability value for exceeding 15 m/s.

A value for SD_i as a consequence of a 20% standard deviation in the estimated $V_{\mathrm{PED,IS}}$ values was obtained by studying the effect from an appropriate modification of the $C_{\mathrm{V}}(\beta)$ values.

With a random generator a series of 12 numbers was generated from a normal distribution with a mean value of 1.00 and a standard deviation of 20%. These numbers were used to get a modified set of $C_{\mathrm{V}}(\beta)$ data for each measuring station. This process of getting a series of 12 numbers from a normal distribution was done

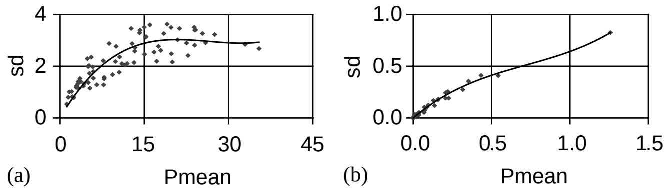

Fig. 2. Uncertainties in the calculated probability values of exceeding a wind speed threshold (a) $V_{\mathrm{THR}} = 5\,\mathrm{m/s}$; (b) $V_{\mathrm{THR}} = 15\,\mathrm{m/s}$.

10 times (10 different series with 1.00 as mean value and 20% standard deviation). Each station thus obtained 11 $C_{\mathrm{V}}(\beta)$ series (one original and 10 modified), 11 values for the probability $P\{V_{\mathrm{PED,IS}} > 5\,\mathrm{m/s}\}$ and 11 values for the $P\{V_{\mathrm{PED,IS}} > 15\,\mathrm{m/s}\}$.

For each measuring station the average value $P_{\mathrm{AVG},i}$ and standard deviation SD_i of the $P\{V_{\mathrm{PED,IS}} > V_{THR}\}$ values were calculated for $V_{\mathrm{THR}} = 5$ and $15\,\mathrm{m/s}$.

The results are presented in Fig. 2.

This example shows that the P_i can be assessed with a standard deviation according to Fig. 2.

With $\mathrm{SD}_i = 3\%$ for wind comfort assessment ($V_{\mathrm{THR}} = 5\,\mathrm{m/s}$; Fig. 2a) and the demand that $P_{\mathrm{MAX}} = 20\%$, the above discussion implies that a wind tunnel simulation should demonstrate that $P_{\mathrm{MEAN},i} < (20 - 1.6 \times 3)\%$, or $P_{\mathrm{MEAN},i} < 15\%$ to a 95% confidence limit.

With $\mathrm{SD}_i = 0.4\%$ for wind danger assessment ($V_{\mathrm{THR}} = 15\,\mathrm{m/s}$; Fig. 2b) and the demand that $P_{\mathrm{MAX}} = 0.5\%$, the above discussion implies that a wind tunnel simulation should demonstrate that $P_{\mathrm{MEAN},i} < (0.5 - 1.6 \times 0.4)\%$ or $P_{\mathrm{MEAN},i} = 0.0\%$ to a 95% confidence limit.

7. Conclusion

Estimation of IS pedestrian level winds is loaded with errors of various kinds. A conservative estimate of the standard error of the pedestrian level wind speed in the built environment is 20%. Consequently, the standard error in the probability that the local wind speed exceeds a threshold value is given by Figs. 2a and b.

A complete discussion of the accuracy of wind tunnel simulation of local wind speed is not yet possible. In particular the technical and aerodynamical errors involved in the simulation are not sufficiently documented. Also the uncertainty in the threshold values for wind comfort and safety as well as the determination of the local turbulent intensity are neglected in the present discussion. A tentative conclusion is that an evaluation of a building plan with a wind tunnel simulation is feasible, but the errors involved should be taken into account while formulating the required probability that local wind speed exceeds a threshold value.

References

[1] R. Sasaki, Y. Yamada, Y. Uematsu, H. Saeki, Comfort environment assessment based on bodily sensation in open air: relationship between comfort sensation and meteorological factors, JWEIA 87 (2000) 93–110.

[2] Th. Stathopoulos, H. Wu, J. Zacharias, Field survey on outdoor human comfort in urban climate, in: Larose, et al. (Eds.), Wind Engineering into the 21st Century, Balkema, 1999.

[3] Y. Shimoda, M. Mizuno, Evaluation of the thermal environment in an outdoor pedestrian space, Atmos. Environ. 30 (1996) 497–505.

[4] J. Wieringa, Updating the Davenport roughness classification, J. Wind Eng. Ind. Aerodyn. (1992) 41–44, 357–368.

[5] ASCE, Wind Tunnel Studies of Buildings and Structures, ASCE Manuals and Reports on Engineering Practice No. 67, 1999.

[6] M.H. de Wit, J.A. Wisse, Wind data analysis in the center of Eindhoven, Proceedings of the 3EACWE, Eindhoven, 2001.

[7] N. Isyumov, Full-scale studies of pedestrian winds: comparisons with wind tunnel and evaluation of human comfort, restructuring: America and beyond, Proceedings of the Structures Congress XIII, 1995, pp. 104–107.

[8] G.Th. Visser, J.W. Cleijne, Wind comfort predictions by wind tunnel tests: comparison with full-scale data, JWEIA 52 (1994) 385–402.

[9] C.D. Williams, R.L. Wardlaw, Determination of the pedestrian wind environment in the city of Ottawa using wind tunnel and field measurements, J. Wind Eng. Ind. Aerodyn. (1992) 41–44, 255–266.

[10] S. Murakami, K. Uehara, K. Deguchi, Wind effects on pedestrians: new criteria based on outdoor observations of over 2000 persons, in: J.E. Cermak (Ed.), Wind Engineering, 1979, pp. 277–278.

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Williams, C.D., Wardlaw, R.L.

The Ottawa wind study: modelscale and fullscale measurements of the pedestrian wind environment
(1989).

Abstract

A scale model wind tunnel study of a downtown area was conducted to determine pedestrian level wind conditions throughout the central area of the City of Ottawa, Canada. Pedestrian level winds were measured at 615 locations. In addition, windspeeds were measured above three selected model buildings. Full scale wind measurements were made at the city airport and simultaneously above the same three buildings. The study objective was achieved through the combination of model scale and full scale wind measurements with the long term wind statistics from the airport to predict the windspeeds which will occur with specified probability at each of the 615 locations. (A)

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Canada, Ottawa, Urban Areas, Wind Fields, Wind Measurements

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