

Wind Chapter Best Practice Guidance



Figure 1 Evening Post photograph 1971

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1.0 Purpose of this Best Practice Guide

This guide explains how the wind rules and standards in the Wellington District Plan apply to new building developments. It also describes the simple wind engineering principles that relate to meeting the District Plans Wind Policies, in particular those relating to early consideration of wind in design of in order to achieve the City's objectives of reducing the adverse impact of wind on public spaces. It therefore describes the features of a building that affect wind flows and the mitigation strategies that can be used to minimise adverse wind effects from a building development.

This guide is not intended to dictate how buildings should be designed. Rather, it outlines the basic wind effects caused by buildings and shows how particular features can cause or alleviate problems. The Quantitative Wind Study required under Wind Rule WIND-R1.4 (Section 88 information requirements and Appendix 8 WIND-A1) is intended to allow design freedom whilst requiring the submission of proof of the likely actual impact of a development, given its local context, rather than setting arbitrary height or building bulk rules. The guide is focused on avoiding problems through sound design of the building form. The goal is to avoid the late addition of aerodynamic devices such as verandahs to the design, because these devices are seldom as effective as good design of the building form itself.

The guide provides a brief introduction to wind and to the management of wind effects from proposed new buildings for planners, developers and building designers. It is not intended to replace the advice of wind specialists that is needed for environmental assessments of wind effects. 'Rules of thumb' are provided to help quantify the general wind effects of simple building forms. These are intended also to provide wind specialists with a consistent basis for providing a qualitative wind assessment under Wind Rule WIND-R1.4 (Section 88 information requirements and Appendix 8 WIND-A2).

2.0 Introduction

2.1 Wellington's wind climate/environment

Wellington is well-known for its windy environment. Strong wind gusts over 65km/hr are experienced in Wellington on average about 160 days a year, compared with 90 days in Invercargill, 70 in Paraparaumu, 60 in Christchurch or 50 in Auckland. The effects of Cook Strait and the hills around Wellington produce prevailing winds in the city which are either northerly or southerly. Northerlies are more frequent than the southerlies, but both can produce equally severe winds.

Wellington is significantly more windy than other international cities that have similar wind rules for urban development, such as London, San Francisco, Boston, and Toronto. The average wind speeds in London, for example are half those in Wellington. San Francisco experiences average wind speeds around 10% less than Wellington's lowest 6 month average, and are 50% less than Wellington's average over the whole year. Boston is the windiest of these cities and has an average for the year 25% lower than Wellington.

These wind speeds are measured 10m above the ground and therefore are twice the speed that would be experienced by a person standing on the ground. In the 1970s wind measurements established that wind speeds 10m above Wellington Airport are the same as wind speeds 150m above Wellington City, so in the City pedestrian level wind speeds will be less than a quarter the wind speeds reported at the airport. However, buildings can bring the upper level winds down to the street creating localised windy areas.

2.2 The basics of wind flow

In general, the wind speed increases with height in the first 150-500m above the earth's surface. The roughness or smoothness of the ground changes the rate of increase with height. At the same height above the ground, the average speed is greater at a site with low roughness (*Figure 2*) than at a site with higher roughness (*Figure 3*). Therefore, an aerodynamic anomaly such as a building, which is much taller than its surrounds, will produce higher wind speeds in open country than in a city. However, the likelihood of such anomalies is far greater in the city.



Figure 2 Flat open country - Low probability of aerodynamic "anomalies"

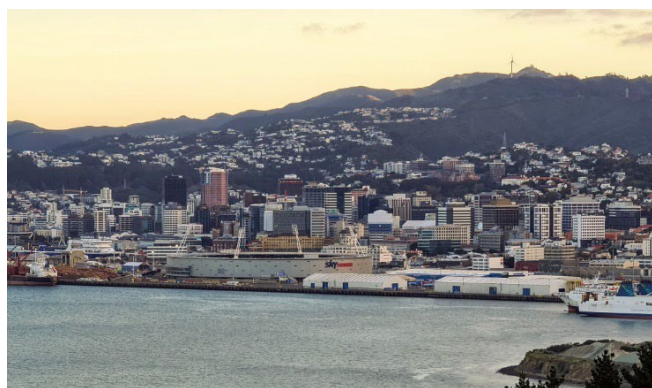


Figure 3 City centre has a high probability of aerodynamic "anomalies"

2.2.1 The built environment

Poor aerodynamic design of some buildings in Wellington has made the already strong prevailing wind conditions intolerable. These buildings have created street environments where walking can be not just uncomfortable but dangerous. The occasional publicity given to pedestrians being blown

over, or historical examples of ropes being placed along pavements for pedestrian safety (up to the 1980s, as shown in *Figure 4*), highlights the seriousness of the problem but does not reflect the extent of the problem.



Figure 4 A Safety Rope in Courtenay Place (Source: Evening Post Newspaper/28 August 1970/3679/10A-F. Alexander Turnbull Library, Wellington, New Zealand. <http://natlib.govt.nz/records/22736399>)

The adverse wind effects a building can create was highlighted in the 1920s with the introduction of the 30m tall Hope Gibbons building into Wellington’s otherwise rather low-rise 2-4 storey environment. Newspaper articles regularly reported personal injury to people, which resulted from their exposure to strong wind gusts induced by this building. For example, a Miss Clarke is reported in the Evening Post 14 March 1945 suffering “...a lacerated wound to the back of her head, [and] a fractured left thigh...” or a Mrs Woolf whose “...right wrist was broken, and she sustained bruises and abrasions and shock...” as reported in the Evening Post on 26 November 1936. Without the building, the winds were high. With the 30m high building (relatively small by modern standards) the wind became far stronger, gustier and more unpredictable.

Wind gusts exceeding 54km/hr have a significant effect on pedestrians. In wind tunnel tests women and children were removed from the testing regime for gusts over this speed. Gusts above 72 km/hr make wind conditions totally unsuitable for walking and cycling. Wind gusts up to 83 km/hr have been recorded in Wellington City streets.

It is not sufficient merely to prevent winds that could knock people to the ground or blow them into the path of vehicles. People also expect most outdoor areas to be liveable and enjoyable for most of the year. The aim is also to create environments that allow people to make the best possible use of their city, which includes both outdoor and indoor spaces. Parks and other areas used for sitting or relaxing, such as outdoor cafes, require wind conditions to be substantially better than ‘safe’.

~~Wellington City Council’s approach to development is stated in the District Plan’s Wind Chapter’s Objective WIND-O1: “The adverse impact of wind from new developments, additions and alterations on public spaces is managed to: 1. Provide comfortable conditions for pedestrians, whilst acknowledging that not all wind effects can be mitigated; 2. Ensure that new developments, additions and alterations do not generate unsafe wind conditions in public spaces and, where possible, ameliorate existing unsafe wind conditions; and 3. Prevent the gradual degradation of Wellington’s pedestrian wind environment over time.”~~

~~The District Plan has specific wind rules and standards that clarify how “the adverse impact of wind” are to be interpreted and controlled. Specifically this means:~~

- ~~1) that existing dangerous conditions are mitigated where possible (Standard WIND-S1);~~
- ~~2) that no new areas exceeding the danger criterion are created (Standard WIND-S1);~~
- ~~3) that the cumulative effect of new developments does not progressively degrade the pedestrian wind environment (Standard WIND-S2); and~~
- ~~4) that public spaces listed in the Appendix 9 of the District Plan have comfortable wind conditions (Standard WIND-S3).~~

2.3 Effects of building form on ground-level wind conditions/environment

Buildings that are exposed to wind induce changes in local ground-level winds, which can make activities such as sitting, strolling, shopping, or entering a building uncomfortable and even dangerous. In an open environment, where the building stands alone, the taller the building, the more wind is accelerated at pedestrian level. In an urban environment, the surrounding buildings have a huge effect on the exposure of a new development to wind. For this reason, general guidelines can risk either exaggerating or underestimating the effect of a proposed building. This is where Quantitative Wind Reports have great value: predicting the interactions of the urban form with the wind and with the development.

Building form and detailing can greatly affect wind-flow patterns and speeds. With an appreciation of how winds flow around buildings, designers can avoid creating high wind speeds at ground level. This is an especially important consideration for buildings that will be exposed to prevailing winds, and those near significant sites such as parks. The guidance in this document is based upon many systematic wind tunnel tests conducted at the CSTB wind tunnel facility in France in the 1970s. These identified the likely proportional increases in pedestrian wind speeds resulting from many different individual building forms, and the corresponding likely reductions in wind speed resulting from various building design features and street level wind breaks.

2.3.1 Considering wind early in the planning and design phase

Wind will need to be considered early in the planning and design of a development when the site is exposed or the building will be significantly higher than its surrounds, as the development is likely to impact the surrounding wind conditions. Internationally (*Figure 5*) and locally (*Figure 6*) it is possible to observe the effect of strong pedestrian-level winds on the financial and operational success of some new buildings.

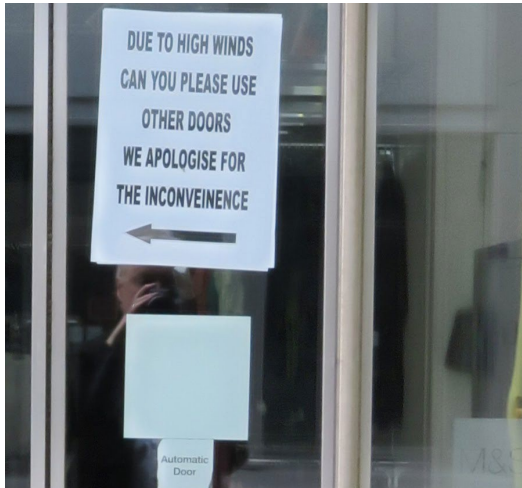


Figure 5 Sign on the door of the Marks and Spencer store opposite the notorious "Walkie Talkie" 40 storey building at 20 Fenchurch St, London



Figure 6 Sign on the door of Mojo cafe in the Asteron building in Wellington, displayed during northerly winds

For a resource consent application required through the Wind Chapter's rules, a Qualitative wind assessment (a desktop review based on expert opinion of a suitably qualified and experienced person) or a Quantitative wind report (detailed study based on wind tunnel testing or computer modelling) is required. The assessment or report is needed to fully understand complex wind flows generated by the development and the surrounding buildings.

The Qualitative assessment is less definitive and may therefore lead to more design changes than the Quantitative report, to provide sufficient confidence that the proposed design will comply with the Wind Standards. It is expected that a Qualitative wind assessment will be based on the best possible evidence of the existing wind conditions at the site, which might include using data from previous wind tunnel tests, or measured site data. The wind effects of the development should be estimated from the wind accelerations documented in this guide (refer section 5 to 8) for structures similar to the proposed design. The wind assessment will document how the design of the overall building form has dealt with possible problems. The addition of a verandah or a wind break is normally an insufficient response.

3.0 Wind controls in the District Plan

3.1 How the Wellington City District Plan wind controls work

Planning controls on the wind effects of new buildings and additions and alterations are set out in the Wind Chapter of the District Plan (under Part 2 District Wide Matters section of the Plan). To be consistent with the National Planning Standards, the wind provisions are included in a new standalone chapter, which sets out the previous wind requirements in a different format.

The technical requirements and reporting for wind effects have not changed significantly, but the thresholds where wind effects must be considered have been reduced slightly. Matters of discretion are now clearly listed in the wind rules, along with the information that must be provided. Assessment criteria are listed for each wind standard to guide planners when a standard is breached. Best Practice Guidance has been updated for the new chapter.

The wind chapter of the District Plan contains objectives, policies, rules and standards and is supported by the Wind Chapter Best Practice Guidance (situated in Appendix 14 of the District Plan).

The Objective and Policies describe the high level outcomes relating to wind effects sought by the Council. They help interpretation of the Rules or Standards if there is uncertainty for resource consent planners when assessing a development application which triggers wind rules. They are also used by Wellington City if discretion needs to be applied to over-ride a Wind Standard. A standard may be over-ridden when other beneficial effects also accrue, or when the observed accelerations are in areas infrequently used by pedestrians but other areas around the same site that are high pedestrian use are made much better.

The rules and standards provide more detail than the objectives and policies, and are generally measurable.

The rules set out:

- the zones where the Wind rules and standards apply;
- the circumstances when a development is either a permitted activity or is restricted discretionary activity under the rule framework;
- the Wind standards that apply;
- the matters of discretion when the wind standards are not met; and
- the type of assessment and information that is needed as part of a resource consent application.

The Standards contain the most technical detail, including:

- what wind conditions are acceptable (i.e. evaluation criteria), covering the safety, comfort and the deterioration in wind conditions with a new development or addition or alteration; and
- assessment criteria that help to apply planning discretion when a standard is not met..

The safety and comfort criteria in the Wind Standard are based on criteria that are commonly used in many cities around the world. The safety standard applies to all the zones where the Wind Rules apply, while the comfort standard only applies to significant parks and recreational spaces that are specified in the District Plan. Elsewhere, comfort is controlled, in part, by the general deterioration standards, which limit the gradual worsening of wind conditions in an area as a series of developments occur.

The general deterioration standards apply to all parts of Wellington where the Wind Rules apply and are intended to reduce the likelihood that several developments over time worsen the wind to the point where the street has wind conditions that are unpleasant or dangerous.

3.2 Triggers for wind controls

Wind effects created by a development only need to be assessed against the Wind Rules and Standards when a development exceeds the thresholds listed below, which trigger the requirement for a wind assessment or wind study to be provided to the Council. The trigger point does not correspond to when wind effects start to occur, but is simply a practical threshold when the wind effects will usually be significant enough to warrant investigation.

~~City Centre Zone, Metropolitan Centre Zone, Special Purpose Port Zone, Special Purpose Port Zone and Special Purpose Waterfront Zone trigger:~~

- ~~• when building height is greater than 20 metres; or~~
- ~~• when an addition is greater than 8 metres in height; or~~
- ~~• when a rooftop addition is more than 33% of the existing building volume and is setback from all sides adjacent to public spaces by at least 5 metres.~~

~~Local Centre Zone, Neighbourhood Centre Zone, Special Purpose Hospital Zone and Special Purpose Tertiary Education Zone trigger:~~

- ~~• when building height is greater than 12 metres; or~~
- ~~• when an addition is greater than 4 metres in height; or~~
- ~~• when a rooftop addition is more than 33% of the existing building volume and is setback from all sides adjacent to public spaces by at least 3 metres.~~

These thresholds correspond to buildings that generally produce significant changes in the surrounding wind conditions. The City Centre Zone etc. thresholds are larger than the Local Centre Zone, Neighbourhood Centre Zone, Special Purpose Hospital Zone and Special Purpose Tertiary Education Zone thresholds because the other larger buildings in the City Centre Zone etc. typically provide greater shelter to smaller nearby buildings. However, these triggers are a crude approximation of the wind effects at specific sites or from specific buildings, so the Wind Rules allow for some discretion and relaxation of the reporting requirements if a site is exceptionally sheltered or a building design is expected to have an exceptionally low impact on wind conditions. ~~In these situations, a Qualitative wind assessment (i.e. wind expert opinion) may be accepted in lieu of a Quantitative wind study.~~

~~For the City Centre Zone, Metropolitan Centre Zone, Special Purpose Port Zone, Special Purpose Stadium Zone, and Special Purpose Waterfront Zone, a quantitative wind study will usually be required to show compliance with the wind standards. Council may accept a qualitative wind assessment when a development is likely to have little, if any, impact on wind conditions.~~

~~For the Local Centre Zone, Neighbourhood Centre Zone, Special Purpose Hospital Zone, and Special Purpose Tertiary Education Zone, a qualitative wind assessment is usually all that is required to show compliance with the wind standards. However, if a development is assessed to have a large negative impact on wind conditions, then a quantitative wind study may be required to enable the wind effects of the development to be fully understood.~~

~~It is up to the discretion of the resource consent planner to decide whether a quantitative wind study or a qualitative wind assessment is required.~~ The requirements for quantitative wind studies and qualitative wind assessments are also set out in Appendix 8 of the District Plan.

Examples of buildings that have a negligible effect on pedestrian-level wind conditions, where a desktop assessment should be accepted include:

- a building or addition that is consistent with other building heights in the neighbourhood and is sheltered from all prevailing winds by adjacent upwind buildings;
- an addition that is small in scale compared to the existing building, and incorporates wind mitigation measures such as verandahs, setbacks and breezeways;
- an alteration that is a minor rooftop addition (e.g. Lift or ventilation room) which is setback from all sides of the existing building;
- a structure that does not impede wind flows, e.g., aerials and masts; and
- a building or addition that is consistent with other building heights in the neighbourhood and is separated from all pedestrian areas by adjacent buildings.

3.3 Building configurations

The Wind Standards require the wind conditions around a development to be compared to the existing wind conditions, which means both the existing site configuration and the proposed building configuration will need to be tested and evaluated. This requirement applies to both the Qualitative and the Quantitative wind assessments.

When a development does not comply with the Wind Standards, further testing and evaluation of alternative configurations is required to show that the best practical design for wind has been developed. The design changes that may be needed for wind will depend on the degree to which the Wind Standard is breached and the severity of the wind effects.

Quantitative wind reports and Qualitative wind assessments need to address the relative impact of different building forms on the pedestrian wind environment and any ameliorative additions that are added to the basic building design. For example, acceleration of the wind in the street may be due to wind channelled along the street in a different manner than the existing flow, and be similar whether the building is 20 storeys or 2 storeys in height. In this circumstance, the wind assessment should focus on ensuring pedestrians have safe and comfortable routes past the areas experiencing accelerated winds. But, if the height of the building is the cause of the accelerated winds then the assessment should address the effects of the height of the building.

One notorious submission to Wellington City Council as part of a proposed development stated that the proposed building would have “no worse effect than any other building of a similar bulk”. This submission missed the point of a wind assessment, which is to find the best practical design. To mitigate the acceleration of the wind at pedestrian level, it is likely that the “sail area” that the building presents to the wind would have to be reduced. This guidance not only outlines the potential accelerations of various building and urban configurations, but it also suggests possible improvements that can be achieved through alternative building forms.

The goal of the District Plan is to encourage good design for wind, rather than rely on ‘tack-on’ wind shelter such as freestanding walls or canopies that is needed to mitigate strong winds created by poor wind design.

Sections 5 to 8 of this guide outline design features and wind mitigation that can be used to avoid windy conditions.

3.4 Application of discretion in assessment of wind impacts

Wind conditions around a development need to be considered in light of the expected use of individual locations and areas, as different areas do not necessarily have equal importance to pedestrians. Areas that are heavily used (e.g. entrance ways to buildings, bus stops) or that have high amenity (e.g. outdoor café seating) should be more heavily weighted for benign wind conditions compared to areas that are infrequently used or have little amenity value (e.g. carparks and arterial roads)

Non-complying wind conditions, particularly winds that exceed the safety limits, require careful investigation and mitigation. If increases in gust speeds are balanced by decreases in gust speeds elsewhere, then the assessment of these changes needs to consider both the relative areas that are affected and the pedestrian use/amenity of the respective areas. It is entirely feasible that the wind issues have not worsened overall, but rather they have been moved in position in the street. Designated parks as well as key pedestrian routes through the city are prioritised with regards to ensuring good wind conditions. Therefore, careful consideration is needed, beyond a simple averaging of the wind speed changes across the site, to balance the competing benefits and disadvantages of wind flows that are redistributed by a development.

3.5 Safety

No matter how windy a site is, pedestrian safety is fundamental to the design of new buildings. A development should be designed to minimise the likelihood of danger to pedestrians, and at a minimum, not worsen dangerous wind speeds at street level.

The safety standard for Wellington requires the annual maximum 3-second gust wind speed to not exceed 20 metres/second (72 km/hr) at pedestrian level. The annual maximum 3-second gust corresponds to the highest wind speed that is expected to occur during the windiest hour for each wind direction during the year. The gust is therefore relatively infrequent, but it is indicative of many more, slightly lower, wind gusts that will also occur at other windy periods throughout the year.

Wellington's windy climate, and urban form means that wind conditions in some areas of the city currently exceed safety limits in the District Plan. While high wind speeds are unavoidable in many circumstances, the Wind Rules are written to encourage new buildings to improve existing wind conditions that are dangerous.

3.6 Deterioration of the overall wind environment

Significant changes in wind conditions can gradually occur over time from the cumulative effects of new developments in an area. A gradual deterioration in wind conditions from subsequent development is limited by the Deterioration of the wind environment criteria in the Wind Standard WIND-S2. These criteria limit the allowable deterioration in wind conditions that can occur at individual locations around the development (recognising that some localised change is almost inevitable), and also specify the net change, averaged over the whole area, to be zero. Overall, a neutral or beneficial effect on wind conditions is sought.

This overall deterioration of the wind conditions is measured by the changes in the number of hours that the mean wind speed equals or exceeds 2.5 m/s. This mean wind speed is used in many cities to categorise the suitability of wind conditions for people wanting to sit or relax for long periods.

The criterion for the overall deterioration requires the change in hours per year to be averaged across all of the areas that are affected by a development. To do this, wind speeds must be measured sufficiently far from a development to pick up all the wind speeds changes that occur, and

the averaging of the changes must account of the area that is represented by each measurement. For example, taking 10 measurements at one end of a street, and only 2 at the other end, will not give a good estimate of the extent of changes, nor will the average measured change be representative of the net effect. The Quantitative and Qualitative wind assessments should provide commentary that specifically addresses the overall effect of a development, noting the high pedestrian priority areas, and how representative the averaging process is of specific areas close to and far from the new development. For example, if the area near the building is significantly affected, but the overall effect, taking account of the many other measurement points not affected, then the wind report needs to address this.

3.7 Comfort

The Comfort Standard WIND-S3 limits the amount of time during the year that mean wind speeds of 2.5 metres per second, or more, are experienced within an area, to no more than 20 percent of the time (this equates to 1752, or more, hours per year). This standard only applies to specific parks (these are listed in the District Plan [in Appendix 9](#)). In other parts of Wellington, the wind standard covering the Deterioration of the Wind Environment (WIND-S2) will also be used to maintain comfortable wind conditions where they currently exist.

Wind speed is only one of the factors that affect people's comfort outdoors. On windy days comfort also depends on:

- gustiness (variation) of the wind – notably peak wind gusts;
- the climate and the season;
- the temperature, precipitation, sunlight, shade and humidity;
- what people are doing;
- what people are wearing; and
- the age and psychological state of the individual.

The above factors are beyond the scope of the wind controls in the District Plan and this guide, which defines comfort only in terms of wind speeds. However, these factors have been incorporated into more complex outdoor comfort indices, which are briefly outlined below.

In the 1990s a series of research efforts looked to develop a heat balance model which included all basic thermoregulatory processes, such as physiological sweat rate, enabling the user to predict real values of thermal qualities of the body (Hoppe, 1993; Hoppe, 1999). This work has resulted in the publication of two outdoor thermal comfort indices.

The first is “Physiological Equivalent Temperature (PET)” (VDI, 1998; Hoppe, 1999; Matzarakis 1999). It is based on the “Munich Energy balance Model for Individuals” (MEMI) (Hoppe, 1993). In 2012, the International Society on Biometeorology (ISB) developed the Universal Thermal Climate Index (UTCI) based on a multi-node model of thermoregulation which is thermo-physiologically responsive to all models of heat exchange between body and environment (Jendritzky, 2002).

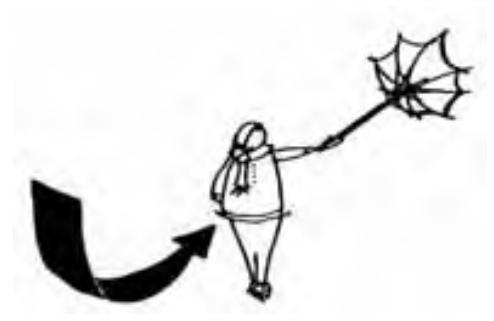
In 2021, Kasun Perera at the Victoria University of Wellington School of Architecture, published his analysis of over 1100 surveys of thermal comfort of people outdoors. He demonstrated that the laboratory-based PET and UTCI theoretical indices have limited practical application. They predict most people surveyed should be comfortable, which is no surprise as they had elected to sit outside when approached during the survey. Unsurprisingly, responses were different for different seasons

and when people had differing expectations of how they planned to use the public space. Perera's Combined Adaptive Factor enables a more holistic comfort standard to be applied to parks.

In Sections 5 to 8, a person's wind comfort is assessed by the percentage increase in wind speed around a building (compared to no building), which corresponds to an increase in their discomfort. Throughout this guide the percentage increase in wind speed is referred to as a percentage increase in discomfort.

Two particular phenomena are not directly included in this measure of discomfort:

- the direction of the flow relative to pedestrians which has an especially critical effect when the flow is ascending (the "reversed umbrella" effect); and
- rapid changes in wind speed which have a significant effect on pedestrian discomfort, especially if the person is moving (such as stepping around the corner of a building from an area of low, to an area of very high speeds in perhaps two paces).



4.0 Qualitative Wind Assessments and Quantitative Wind Studies

A Qualitative Wind Assessment is a desktop review of the effects a building will have on the wind environment, which is based on expert opinion. A Quantitative Wind Report differs from a Qualitative Wind Assessment in that it is based on detailed wind tunnel testing or computer modelling to determine the specific wind conditions at a site and wind effects of a development. The rules or thumb contained in sections 5 to 8 will be most useful for Qualitative Wind Assessments, where site specific or building specific data is not available. When site specific or building specific information is required, then a Quantitative Wind Study will need to be undertaken.

The material in the following sections of this guide describe in general terms the wind interaction of individual building forms with idealised urban forms created by groupings of buildings, and of wind shelter features such as windbreaks. These sections provide general design information on their wind effects in urban spaces. In addition, the information is intended to help designers identify options that could be explored should a Quantitative Wind Study need to identify non-compliant wind conditions in public spaces.

If these design options have not been incorporated into the preliminary design, it is anticipated that the options will be analysed if they are likely to improve the performance of a design. Equally, Council officers can use this information to assess whether all practical measures have been taken to avoid worsening the wind in the city.

For example, if it appears likely from a Quantitative Wind Study that the design of a proposed building is causing accelerations at street level, the study should investigate whether the issue is, say, due to downwash from a tall façade or channelling between buildings. If the height of the façade is the issue, a shorter building should be tested to determine the degree of the wind acceleration due to façade height. Alternatively, if horizontal channelling is the issue, then design options should be investigated which reduce this channelling effect without placing vertical windbreak screens in public spaces.

The role of the following sections in a Qualitative Wind Assessment is far more systematic than for the Quantitative Wind Study. It is expected that a specialist completing an Assessment will quantify the wind effects using the guidance in these sections the standard design situation that most closely resembles the proposed design.

As often as possible the baseline wind speeds estimated in a Qualitative Wind Assessment for an existing site should be based on measurements made at the site, or on the results of previous Quantitative Wind Studies that have been recently completed nearby. The wind accelerations for the proposed design should be derived from the documented accelerations of the closest building form or urban configuration in Sections 5 through 7. Mitigation measures should in turn be based on the practical advice for those building forms in these Sections.

In principle, the goal is to avoid wind accelerations at pedestrian level that require tack-on features that are not part of the basic design, such as free-standing windbreak screens. Where such measures are proposed, their effectiveness should be estimated from the data in Section 8.

5.0 The basics of interaction between individual buildings and wind

Buildings form obstacles to wind flows, causing a positive pressure zone to be formed on the windward face. At the same time, a negative pressure (which forms a suction) zone is created at the sides of the building. An increase in wind velocity occurs where the two zones meet, and the wind flows from the positive to the negative.

Pedestrian-level winds result from a complex reaction between the wind and the building(s), involving the building's shape, size and relationship with other buildings. Different-shaped buildings generate different wind effects.

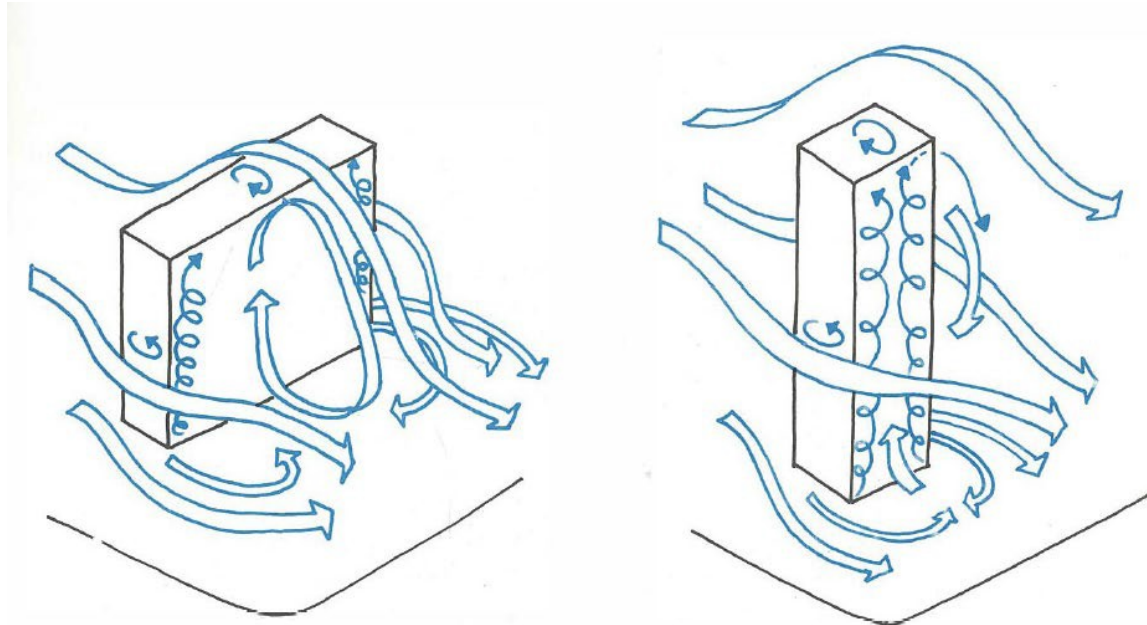


Figure 7 Wind flow around buildings of different geometries.

The best approach to the problem of unpleasant pedestrian wind conditions lies in the placement and design of buildings. Buildings should not be allowed to be designed without regard for their surroundings, and tall slab-sided buildings should not be built in isolation. Attention should be given to the entrances and immediate forecourt area of buildings.

One building placed to windward of another can act as a wind shield, protecting the second building. A tower block rising out of a podium, a building with substantial verandahs around it just above pedestrian height, a building which has vents through it in non-pedestrian areas to channel wind, or a building which is circular or octagonal in shape generates fewer undesirable wind effects. However, even with such designs, it cannot be assumed that further wind analysis is unnecessary, since variations of building design or the immediate environment may combine to worsen wind conditions.

It is very difficult to predict accurately the interaction between the complex, turbulent natural wind flow and a single sharp-edged three-dimensional object like a building. The matter is made immensely more difficult when the building is surrounded by many other buildings that are typically nearby in an urban environment. Currently, the only way to predict a building's wind environment reliably is by way of a Quantitative Wind Study. While computational fluid dynamics (CFD) can be used to indicate the changes in average wind speeds around buildings, there is little evidence that it can yet reliably predict the local turbulence and thus be used to predict wind gusts that indicate

safety issues. Since either approach is costly, the developer is often in a dilemma, undecided whether to:

- undertake a full wind tunnel test before preparing working drawings, and risk having the wind tunnel report invalidated by subsequent design changes; or
- undertake the full wind tunnel test after the preparation of working drawings, and risk the report necessitating major changes to the working drawings.

Sound aerodynamic design early on can avoid the need for time consuming and expensive major revisions.

The following paragraphs summarise the likely effects of isolated buildings of simple basic forms on the ground-level wind environment in their vicinity. The diagrams and the discomfort levels, which are theoretical case studies undertaken overseas, are accurate only for the building configurations shown. In complex urban situations it is much more difficult to predict the wind effects of a new building. This makes expert advice essential.

In general, the larger the mass of a building (especially the height), the greater the disturbance to the pattern of wind flow.

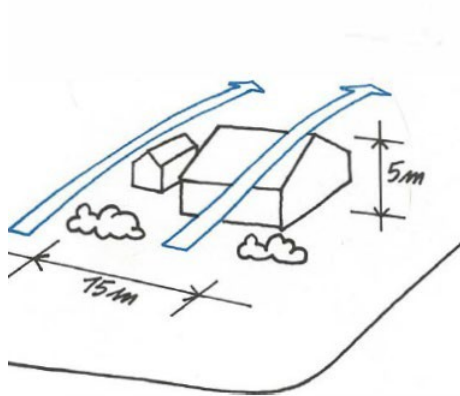


Figure 8 The wind flows over the obstacle without being deflected significantly

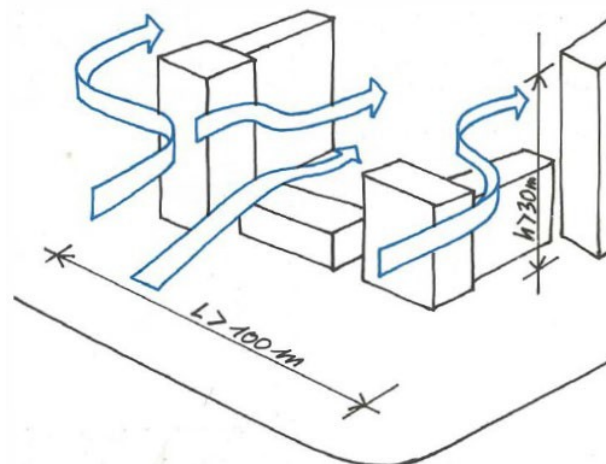


Figure 9 The wind is very strongly deflected and strongly altered by the set of buildings

The wind varies over time, thus, even stationary, a person experiencing wind gusts will be subjected to a wind forces that vary in intensity and direction over time.

This unstable effect constantly forces pedestrians to adapt to a new state and causes the main discomfort for walking and balance, hair styling, the agitation of clothes, the use of umbrellas etc. The level of turbulence in the wind characterises the variability over time.

Consequently, for the comfort criterion in this guide, as well as for the procedures that result from it, we only take into account the discomfort due to the “wind phenomenon”. This is then characterized locally by the average speed and turbulence. Other aspects such as ambient temperature, the psychology of the individual, etc., are not taken into account in this criterion.

It should be recognised that old urban forms, by their high density and similar building heights, create relatively sheltered environments.

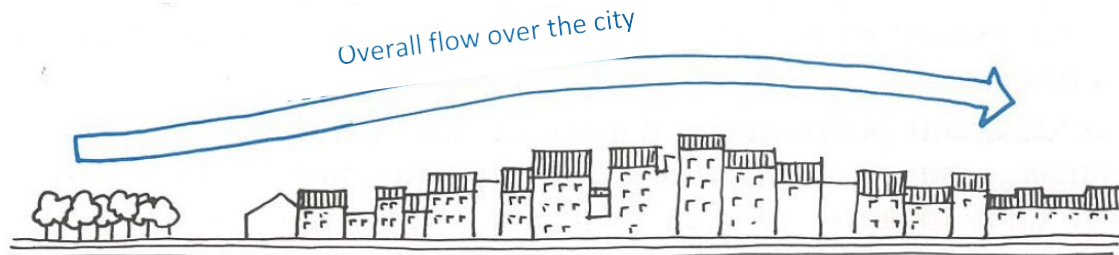


Figure 10: The wind does not penetrate into densely packed buildings

Aerodynamic ‘anomalies’ in an old urban environment are unlikely, except at the foot of tall buildings that emerging above the neighbouring buildings. For example, a 100m tower in an old urban form will cause generate adverse winds at ground level. The diagram below shows significant discomfort will be experienced in the immediate vicinity at the base of the tower (strip of the order of 10 m wide), where the wind is accelerated by 60%.

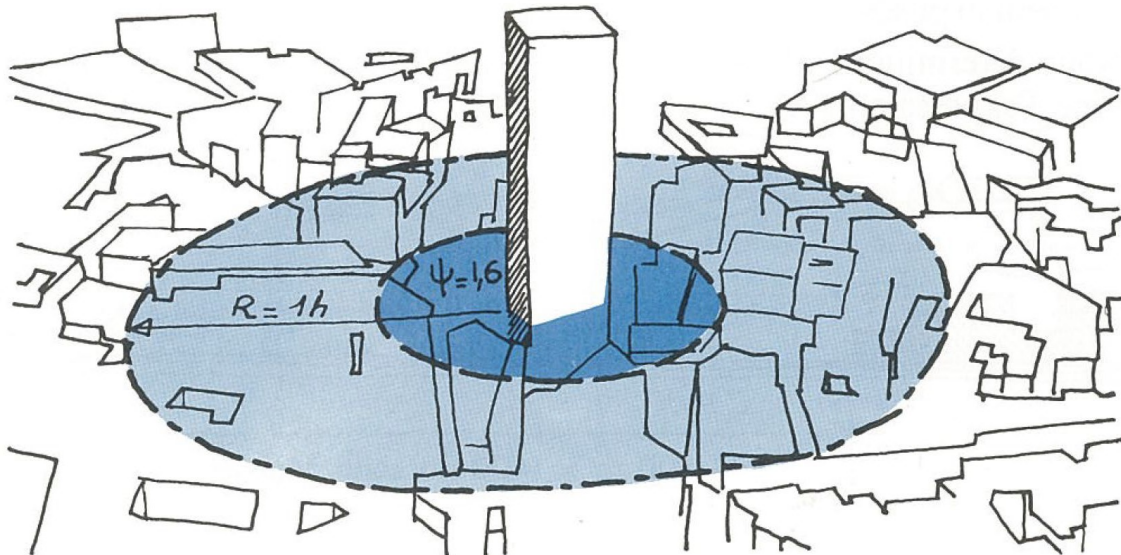


Figure 11: Area at base of a building where discomfort will be experienced by people

Adverse wind effects from a tall building (47 floors, 169m tall) in a relatively open urban environment was reported in Manchester in 2014 (refer <https://www.manchestereveningnews.co.uk/news/greater-manchester-news/gallery/wind-manchester-blows-people-over-6702867>). The tall building and its effect on people in the surrounding streets is shown in the photographs below. The average wind speed in Manchester is roughly half that in Wellington.



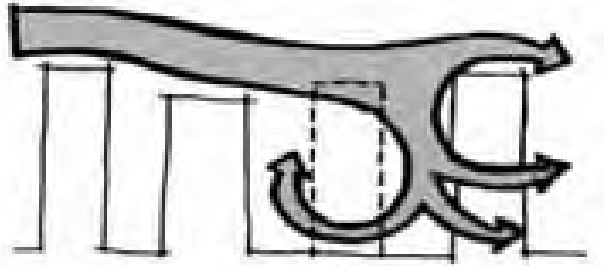
5.1 General guidance for wind design

The following guidance is based on studies of the interactions of idealised buildings and the wind.

Buildings will induce high wind speeds at ground-level if a significant part (that is, one-third the building's height or more) is clearly above the height of buildings located upwind.

Where a new building is planned the design should consider:

- the wind environment created by the surrounding buildings;
- the impact the new building will have on the existing wind patterns; and
- the impact the new building will have on the balance of the site.

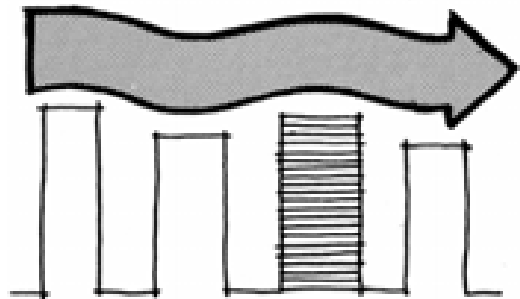


Where there is a likelihood that re-development of adjoining sites or sites within the localised wind environment may occur, designers should consider the potential changes to the wind patterns effecting the new building, and make the design as robust as possible in relation to pedestrian safety and comfort.

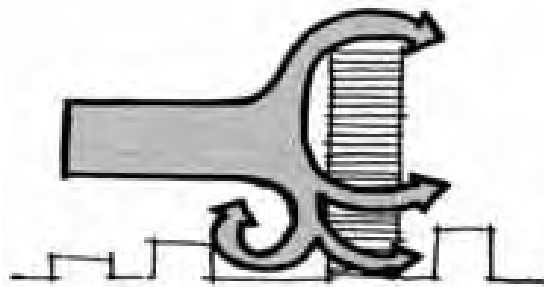
5.2 Site exposure

A building of similar height to its neighbours may be protected from large wind loads and cause minimal pedestrian level wind discomfort. However, this situation is lost when either:

- a building is introduced that is significantly taller than its neighbours; or
- a compatibly-sized building is demolished, and replaced by either a relatively low building or an open space. The degree of increase in discomfort depends upon the scale of the open space created.



The sites where simple form buildings have the greatest potential for creating adverse wind conditions are those in areas with drastic variations in building height. The greater the area of the windward face exposed to wind, the greater the potential problem, because of the absence of shelter from upwind buildings.



A cluster of buildings of similar height will tend to shelter pedestrians within the cluster.

5.3 Rectangular towers and slab blocks

Because the wind speed typically increases with height, the top of a tower is exposed to wind speeds and pressures that are higher than at its base. The higher pressures at the top of a rectangular building force the air to flow down its windward face, so increasing wind speeds at pedestrian level.

5.3.1 Downwash

The taller a building, the greater the pressure difference down the windward face of the building due to the wind speed increasing with height. This leads to a flow of wind down the face of the building driven by this pressure difference. This phenomenon is known as downwash. The height of the building must be greater than 15m for a noticeable effect.

A simple rectangular building will likely have a zone of increased wind speed at the base of its windward face, due to downwash.

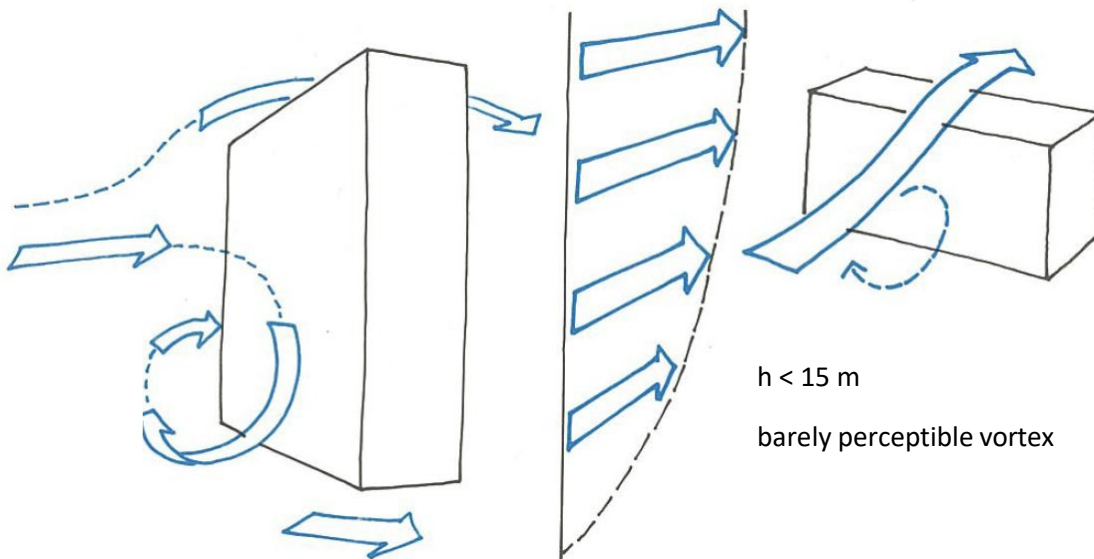
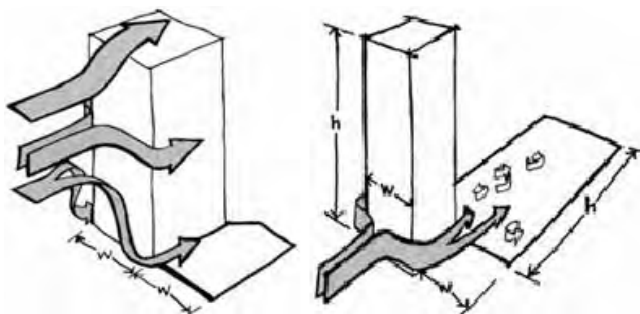


Figure 8 The wind flow mostly crosses over the top of the building where $h < 15m$

For wind incident at right angles to a 60m high rectangular building, the acceleration at the base of a building is over 50%. This disturbance is particularly unpleasant because of the vertical component that the flow in the vortex can have.



The deflected wind flow has the following properties:

- 1) A vortex of reversed wind flow in the centre front of the building;
- 2) Swirling accelerations up to the width of the building either side; and
- 3) Swirling winds in the wake for a distance downwind equal to the height of the building.

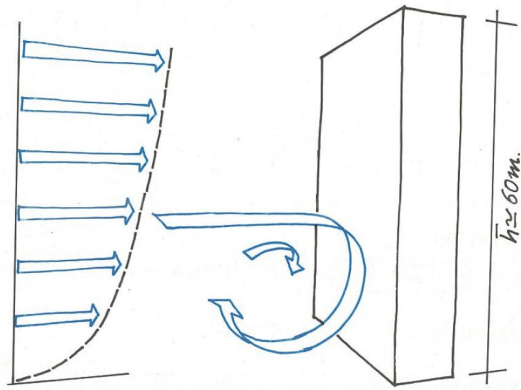


Figure 13: Vortices created at the base of a 60m high building

5.3.1.1 Practical advice

<p>Densify the nearby environment. Introduce deflector awnings / ‘verandahs’.</p>	<p>Introduce porosity into the building above the pedestrian level.</p>
<p>A schematic diagram of a building with a hatched rectangular deflector awning at its base. A blue arrow shows the wind flow being deflected upwards and over the top of the building. The text 'Deflector awning' is written next to the hatched area.</p>	<p>A schematic diagram of a building with a hatched base and a facade consisting of several horizontal perforated sections above the ground level. A blue arrow shows the wind flow passing through these sections. The word 'porosity' is written below the building.</p>



Figure 9 Even with extensive verandahs and a porous façade for the two storey car parking levels above the first floor, the sheer bulk of this building causes significant deterioration in wind conditions on the adjacent footpaths. Featherstone Street, Wellington



Figure 10 Two buildings with porous facades at car parking levels and with pedestrian level verandahs. Lambton Quay, Wellington



Figure 16 Aurora House, The Terrace, Wellington. This building has chamfered corners to reduce the width of the building 'catching' the wind; combined with a large glazed verandah



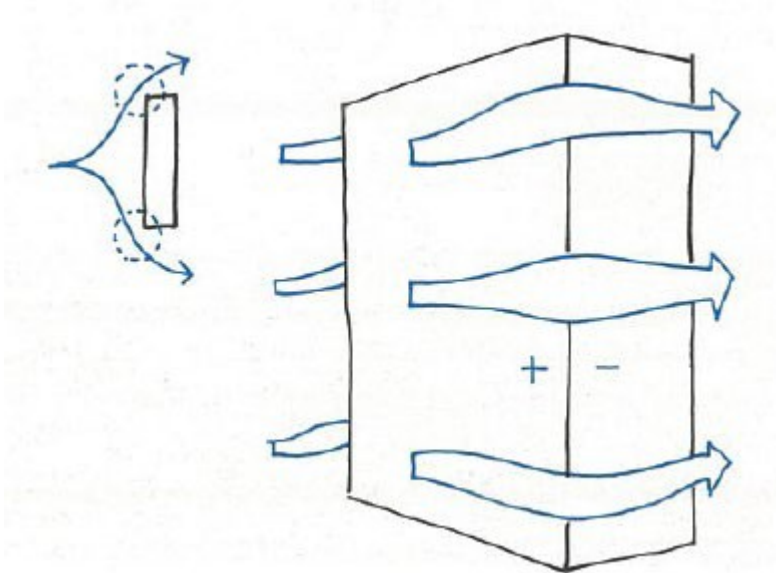
Figure 17 Scale of the space provided by the verandah in Figure 16



Figure 11 Clustered lower buildings nearby have reduced the need for the chamfered corners as they have achieved something closer to situation pictured in Figure 21, The Terrace, Wellington

5.3.2 The corner effect

The worst area where downwash is experienced is at the windward corners of a building. From a wind point of view, therefore, the worst place for a building entrance is on a corner that is exposed to the wind.



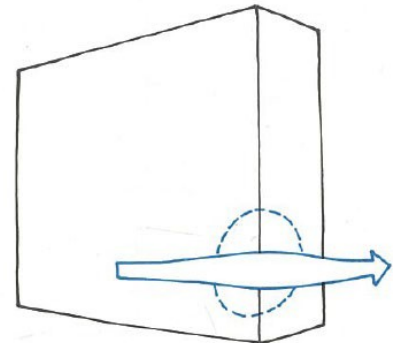
The increase in discomfort levels due to the corner effect can be similar to the range experienced from the downwash effect.

Near the windward corners of a wide low-aspect ratio building the following accelerations are typical (the effect varies with building height),

- a 4-storey building will cause a 20 percent increase in discomfort level
- a 10-storey building, a 50 percent increase

$$\bar{h} = 15 \text{ m} \rightarrow \psi \approx 1,2$$

$$\bar{h} = 35 \text{ m} \rightarrow \psi \approx 1,5$$

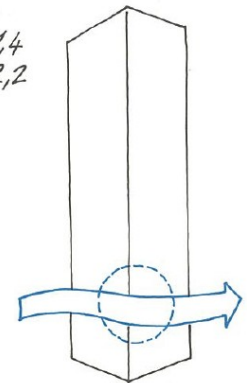


Near the windward corners of a narrow high-aspect ratio building the following accelerations are typical (the effect varies with building height),

- a 15 storey building, a 40 percent increase
- a 35-storey building, a 120 percent increase.

$$\bar{h} = 45 \text{ m} \rightarrow \psi \approx 1,4$$

$$\bar{h} = 100 \text{ m} \rightarrow \psi \approx 2,2$$



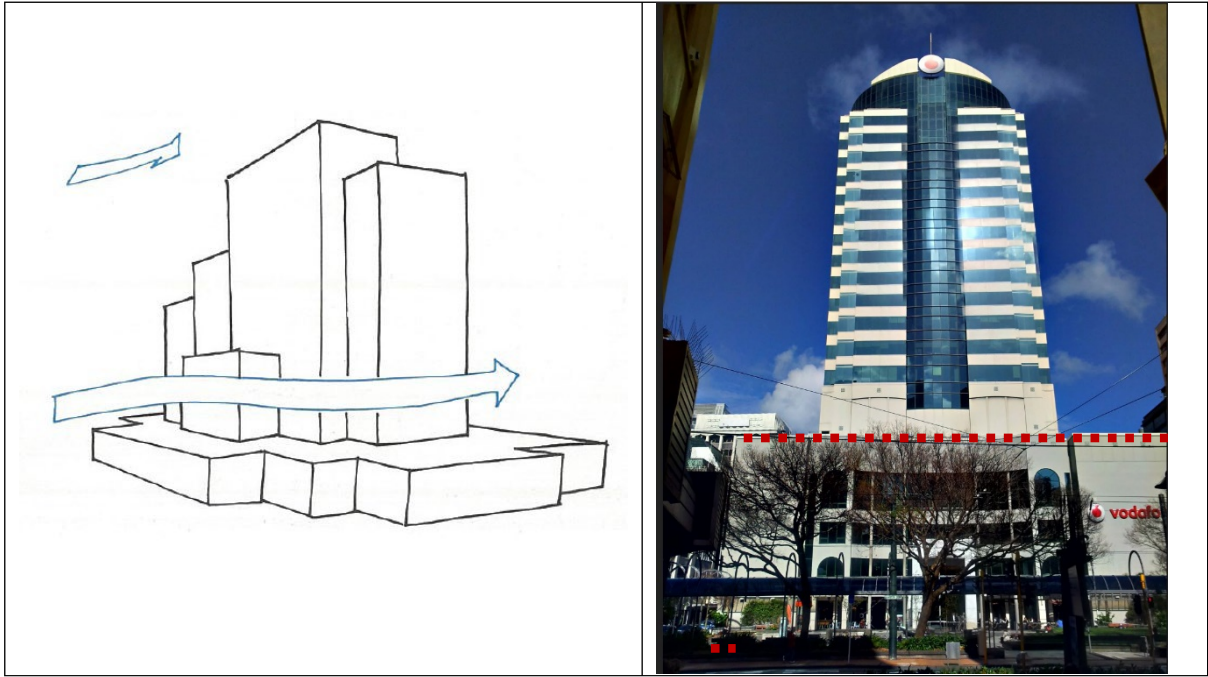
The air concentrated at the base of the windward face of a building flows rapidly from there around the windward corners of the building towards its more sheltered sides and rear. What makes the corner effect worse from a pedestrian point of view is that the transition zone between high- and low-speed winds at these corners is small. Pedestrians crossing this zone encounter, unexpectedly and hence in a potentially dangerous way, sudden changes in wind speed. The greatest wind speeds are generated within a distance equal to the width of the building face.

The following practical advice should be used in early design to avoid the potential problems, and should form the basis for the alternatives assessed in the Quantitative Wind Studies and Qualitative Wind Assessments.

5.3.2.1 Practical advice :

Surround the volume with a ground floor element.

Figure 12 Corner effect mitigated by wrapping lower levels in structure that concentrates the downwash wind well above pedestrians. Wellington.



Surround the tall element with other buildings such as multi-level obstructions.

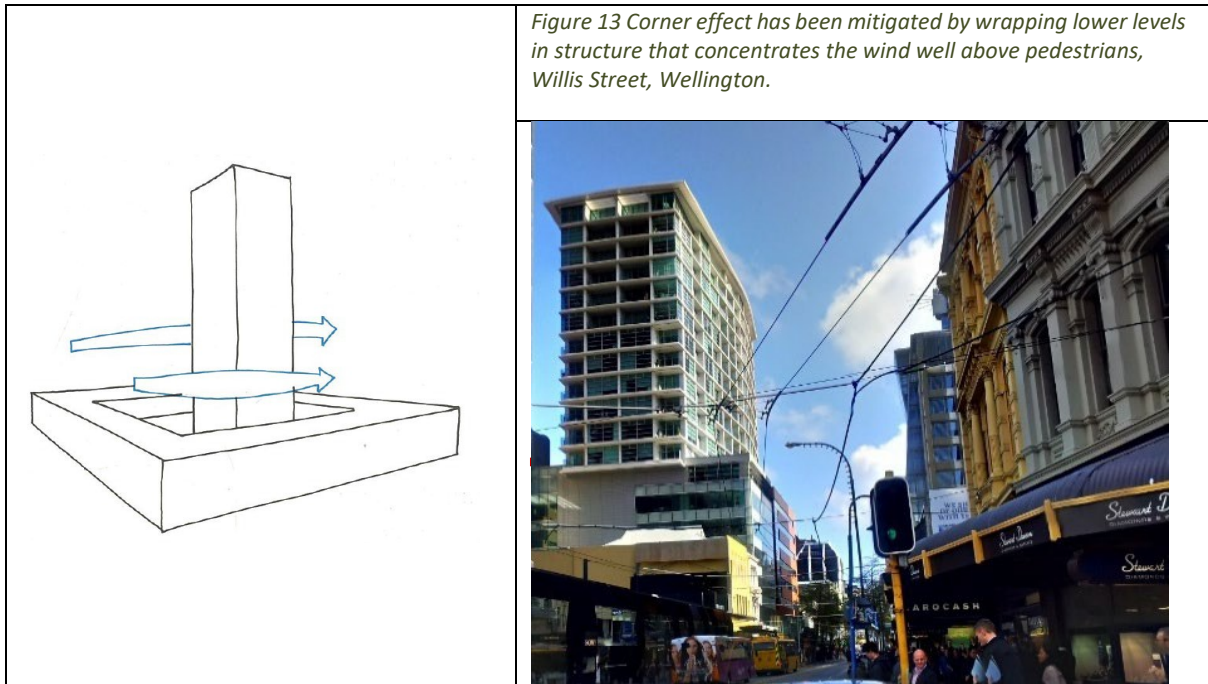


Figure 13 Corner effect has been mitigated by wrapping lower levels in structure that concentrates the wind well above pedestrians, Willis Street, Wellington.

Gradually reduce the height.

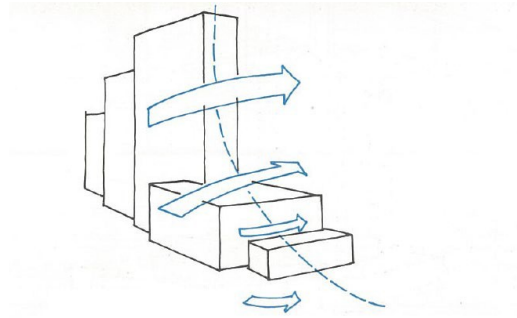


Figure 21 Wind flow is diverted "sideways and up"



Figure 22 The combination of buildings provides the sort of wind diversion illustrated in Figure 21; Manners St, Wellington

Rounded corners decrease downwash

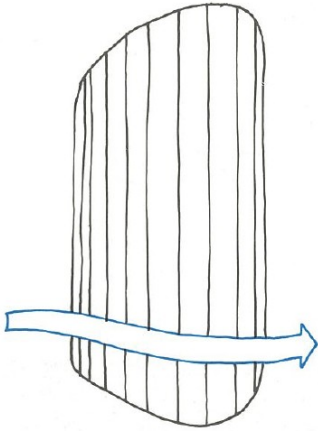


Figure 14 Corner effects of an isolated building are mitigated by 'cloud' plan shape, Bowen Street, Wellington



Figure 15 Corner effects of an isolated building are mitigated by the rounded planform, Boulcott Street, Wellington

Provide porous elements close to the corners.

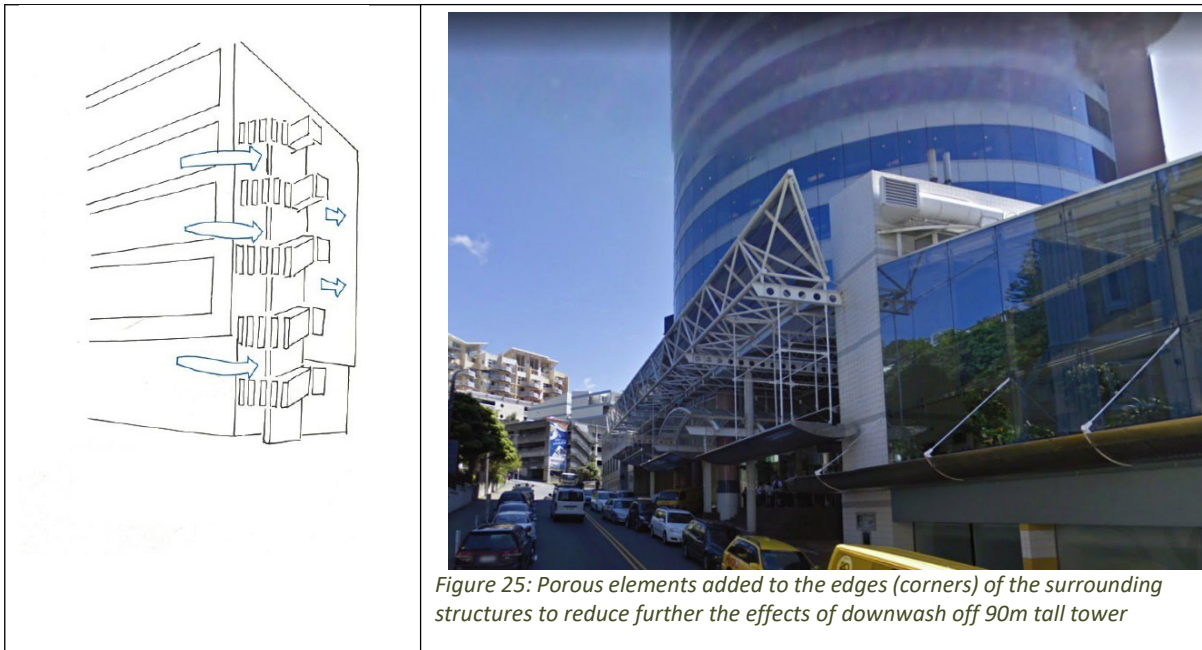


Figure 25: Porous elements added to the edges (corners) of the surrounding structures to reduce further the effects of downwash off 90m tall tower

5.3.2.2 Combining good building design features.

When many of the wind design measures were brought together in the 1980s and used in a building 40m high (Figure 26), it caused far less wind issues than the ~30m high Hope Gibbons building that caused many wind problems from the 1920s until the 1980s. Features include: chamfered corners, which function very much like rounded corners; an open car park level above pedestrians to allow the downwash to dissipate through the building; and an extensive verandah as close to pedestrians as possible.



Figure 16 Chamfered corners of the tower reduce the impact on the wind of a broad flat wall, and are simpler to build than a curved planform; also open first floor car parking diverts wind flow above pedestrians. Victoria St, Wellington

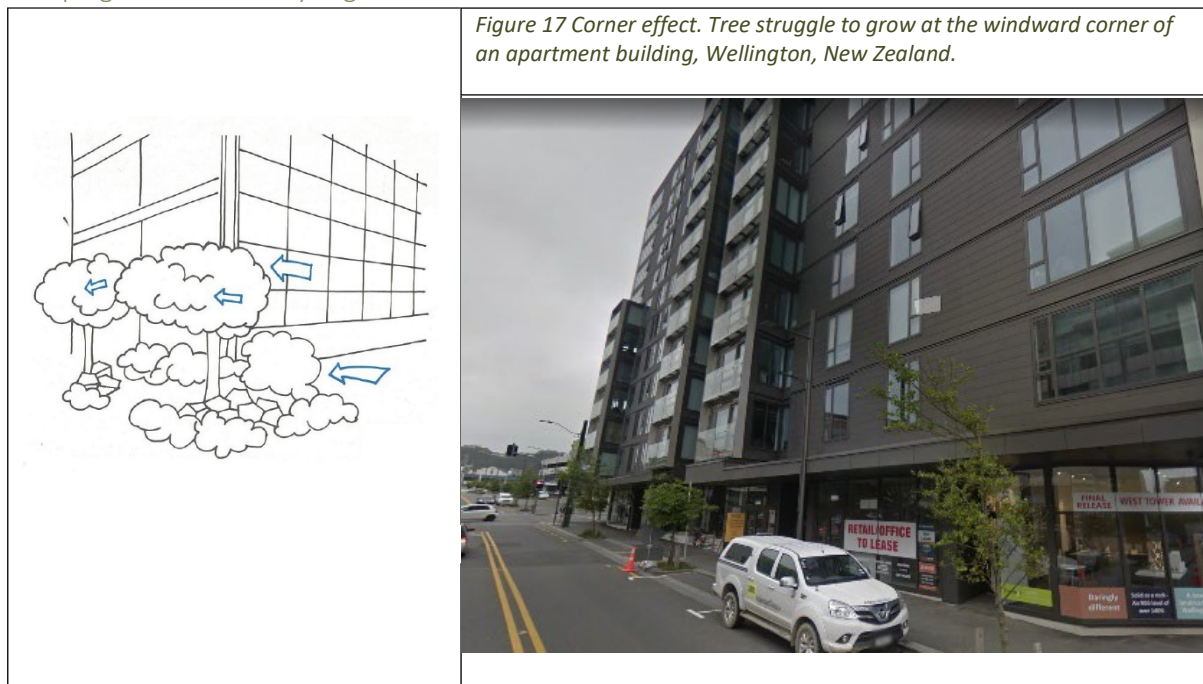
5.3.2.3 Landscaping (vegetation, or low construction) at the corners.

It is common to assume that placing trees as porous elements will reduce the “corner effect”. It is assumed their porosity will smooth the wind flow and the planting will have the added benefit of

moving pedestrians away from the corner. However, there are many practical problems with reliance on planting. These include:

- maintenance (who is responsible in the long term);
- design of the city urban landscape;
- blocking or restricting pedestrian pathways and access; and
- the practicalities of growing trees in windy environment.

Damping of wind flows by vegetation



Another issue that can arise in the planning and development process is miscommunication and misunderstanding between the many disciplines that are inevitably involved in the design of large complex urban buildings. At times, the landscaping that is wind tunnel tested is not what is planted. A landscape architect may have plants installed that will withstand the wind, but they may not provide the shelter required. A relatively tall building London, at 20 Fenchurch Street – the so-called ‘Walkie-Talkie’ building, demonstrates this problem of reality not matching what was tested. Wind tunnel tests showed a continuous row of trees 10m tall, underplanted by other screening shrubs of at least 1m height, would resolve predicted dangerous winds on the corner illustrated in *Figure 28* was. The reality of the trees and planting, illustrated in 2016, has no significant wind mitigation effect whatsoever.



Figure 18 Corner effect. "Walkie Talkie" building, 20 Fenchurch St, London. Proposed trees in a continuous row 10m tall, recommended by wind tunnel testing to reduce dangerous winds at this corner, were never planted. The trees are too far apart and not underplanted as recommended

It is also worth noting that wind conditions around the 20 Fenchurch Street deteriorated for another reason. This was due to a misunderstanding of the way the wind tunnel test results had been written. Wind conditions had previously been suitable for quiet wanders and window shopping but were initially predicted to deteriorate to dangerous winds at the corners. The wind tunnel testing suggested the 10m-tall, planted screen would solve this problem. However, the solution only avoided the dangerous winds. The street was still, with the suggested planting, predicted to be much windier than it had been previously.

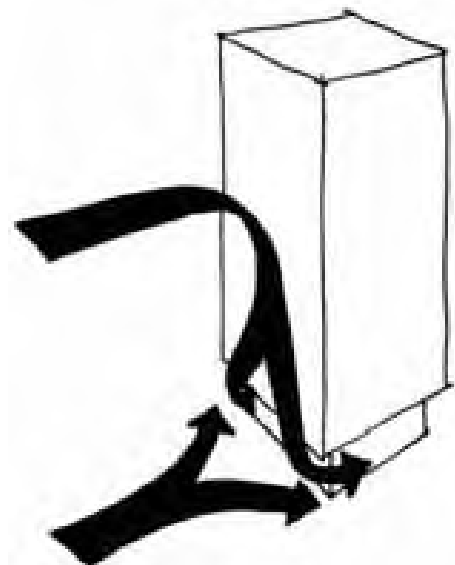
This example illustrates how important it is for plans that are submitted for planning approval are compatible with the results of the wind tunnel tests and assessments. If planting is recommended as wind mitigation in a Quantitative Wind Study or a Qualitative Wind Assessment, then planting of the scale, density and hardiness required should be included not only in the architectural plans, but also in the landscape proposals.

5.3.3 Building setbacks

Setbacks of the ground floor around a building may improve the pedestrian comfort level, but usually worsen it. The effect depends on the depth and height of the setback.

Recessed entries may provide a degree of protection at pedestrian level. The degree of protection depends upon the height and depth of the recess, and the wind patterns experienced locally.

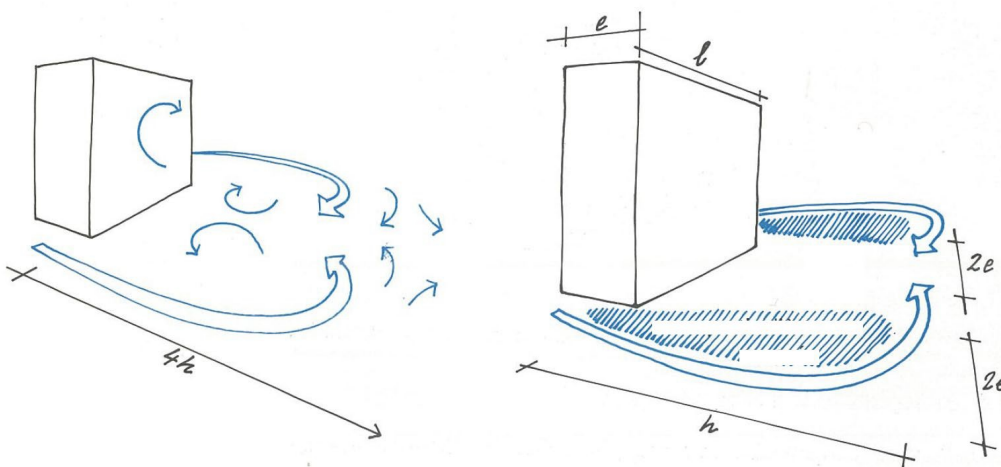
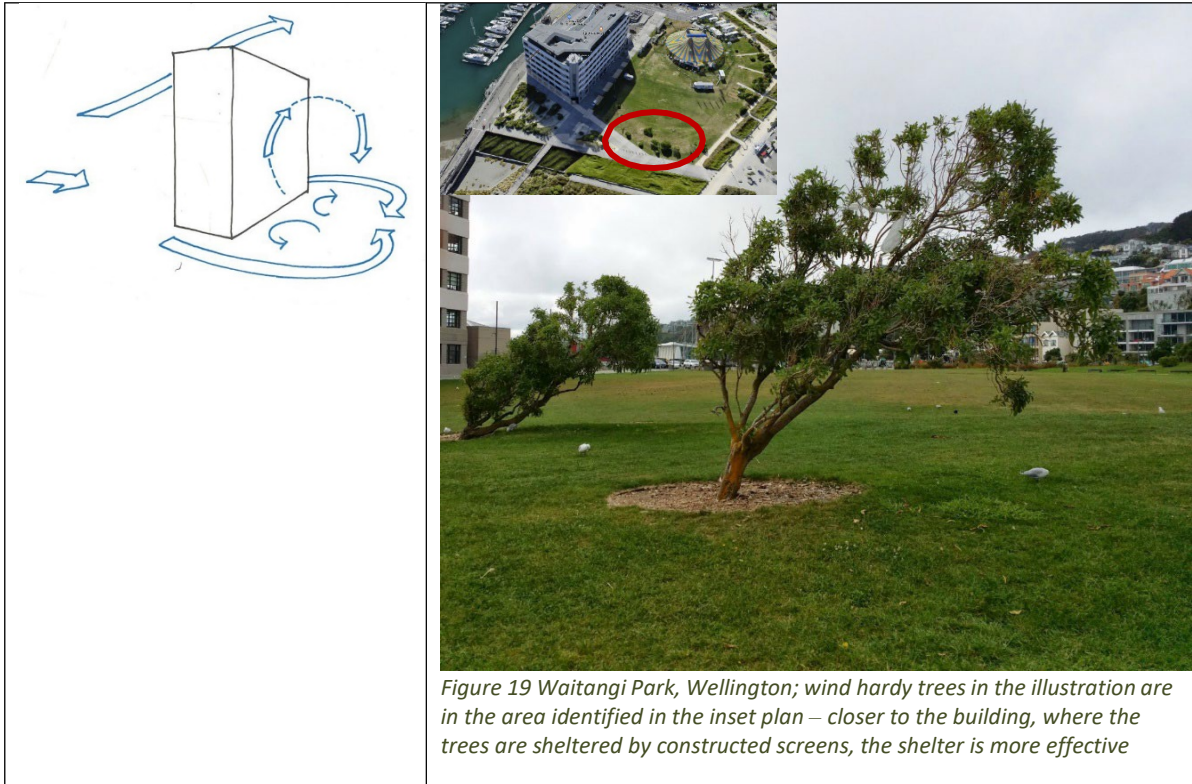
Particular care should be taken when a recessed corner entrance is contemplated as these may accentuate wind effects at corners.



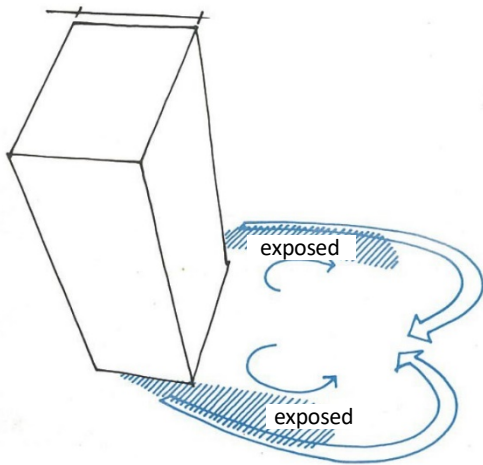
5.3.4 Wake effect

Higher wind speeds and turbulence add to the discomfort felt downwind from buildings. Much of the discomfort occurs as a result of the corner effect, which for 4 to 10 storey buildings, persists for up to 4 times the height of the building downwind of the building and can spread out, as indicated in the diagrams below.

Discomfort levels are worsened by increases in building height. For example, an isolated 60m tower block building causes about a 40 percent increase in the level of discomfort, whereas a 100m building causes a 120 percent increase.

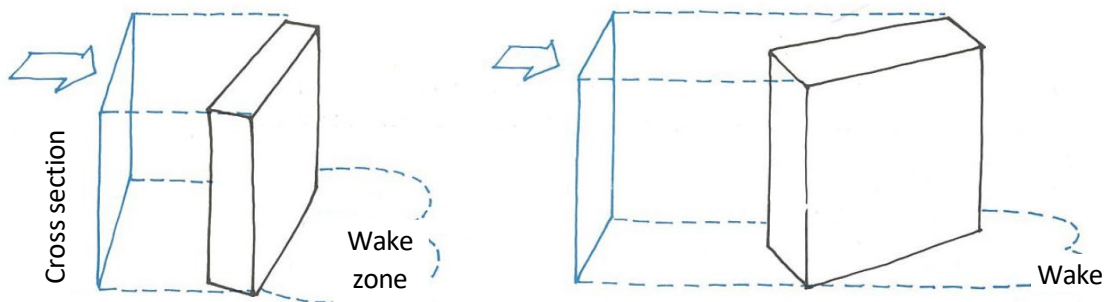


The wake has a characteristic "horseshoe" form. The area particularly affected extends downstream by the height (h) of the building, and extends laterally by twice the depth (e) of the building on both sides of the building.



Each building is different in terms of the discomfort it creates and the area of ground it affects. A 16-storey slab block can increase the discomfort level by 60 percent.

The size of the wake is a function of the cross section facing the incident wind.



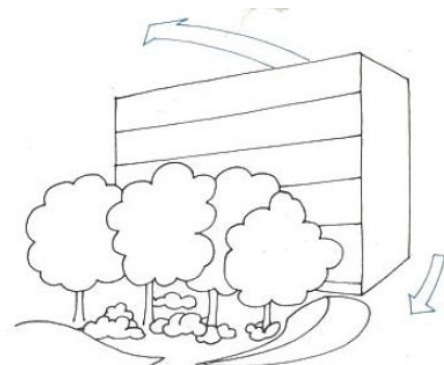
Practical advice

Adverse wake effects are minimised by presenting the smallest cross section of the building to the wind.

Extensive planting can also reduce wake effects.

Care should be taken to ensure that the trees will actually continue grow (*Figure 30*) and provide the required shelter in a windy environment.

The denser the built environment, the more the wake effect is mitigated.



The following examples demonstrate that planting as a solution for strong winds has rarely been successful in Wellington City.



Figure 30 Kate Shepherd Apartments, Wellington, New Zealand. Trees planted by developer as alternative to a canopy wind shelter will never provide the promised shelter, and have become the responsibility of the City Council, not the building owner



Figure 31 "Hamilton Chambers": the trees originally proposed have not established



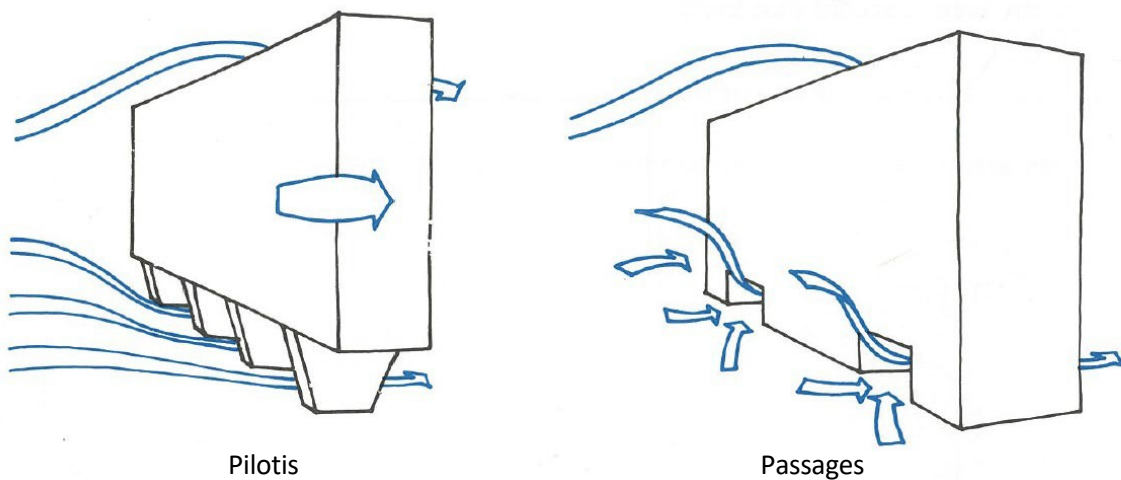
Figure 32 "Hamilton Chambers" Lambton Quay, Wellington, NZ. Proposed tree wind shelter never grew successfully. Now reduced to shrubs that grow but provide none of the promised shelter

5.3.5 Arcades and colonnades

Arcades and colonnades at the base of exposed buildings can provide openings between the higher pressures of the windward face and lower pressures at ground level through which high wind speeds are induced.

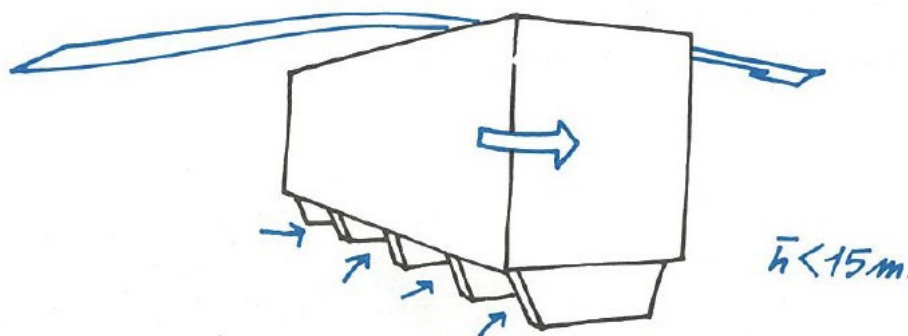
Arcades and colonnades should never be designed as main public access-ways, or as window-shopping precincts unless there is adequate protection from wind.

When there are passages through buildings that effectively connect the high pressure side at the front of the building with the low pressure side at the rear, there can be very significant accelerations of wind through the passageways. This can mean that spaces that might be thought of as 'indoors' experience wind speeds much higher than those experienced *outdoors*.

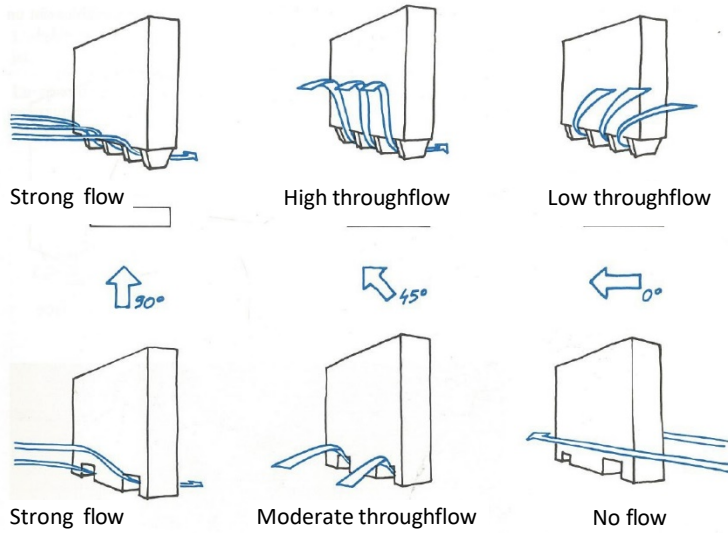


The minimum height of buildings likely to experience significant wind effects from this phenomenon is around 15m.

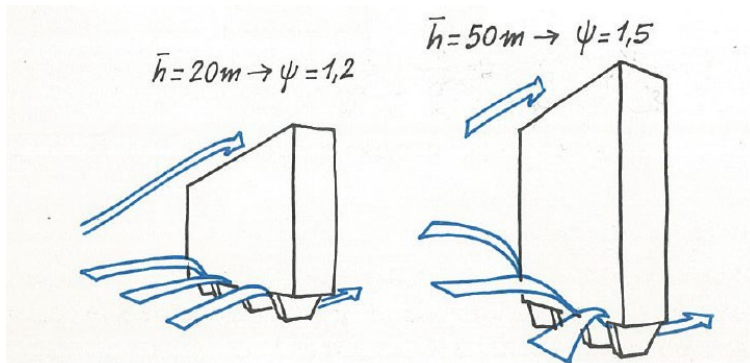
buildings less than 15m high do not make a big enough screen



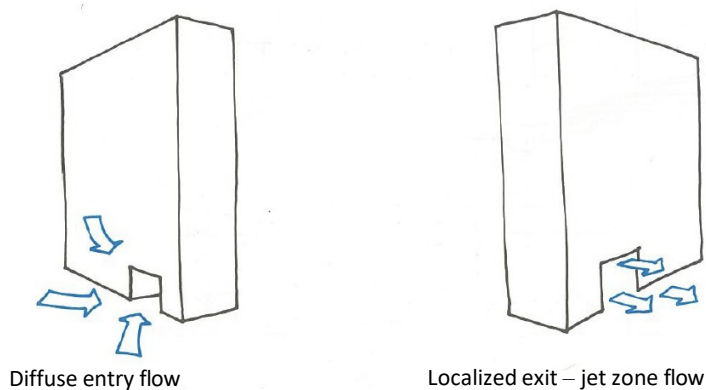
The orientation of the passage through the building affects the magnitude of the accelerations. Also, the nature of the openings underneath the building affects the amount of flow. Where the building is raised on blade-like "pilotis" the accelerations are greater than if there is a corridor cut through the building. Closing these linking passages off with doors may reduce the wind while the doors are closed but they make opening and closing the doors hazardous. Wind lobbies with two opening doors at each end of the passage are seldom effective because to ensure their effective operation, they must be very long (of the order of 10m) to function as intended where the outer door of the lobby is closed before the inner door opens.



The taller the building, the more pedestrian comfort is reduced. For buildings on “pilotis” the accelerations under a building 20m high are expected to be 20 percent, and for a building 50m high the accelerations experienced under the building are 50%.



For the same 50m building, the acceleration of wind in normal passages under the building are likely to be 40 percent.



The discomfort zone is not limited to the passage under the building but continues downstream, in the jet zone, over a volume of the same order as that of the hole.

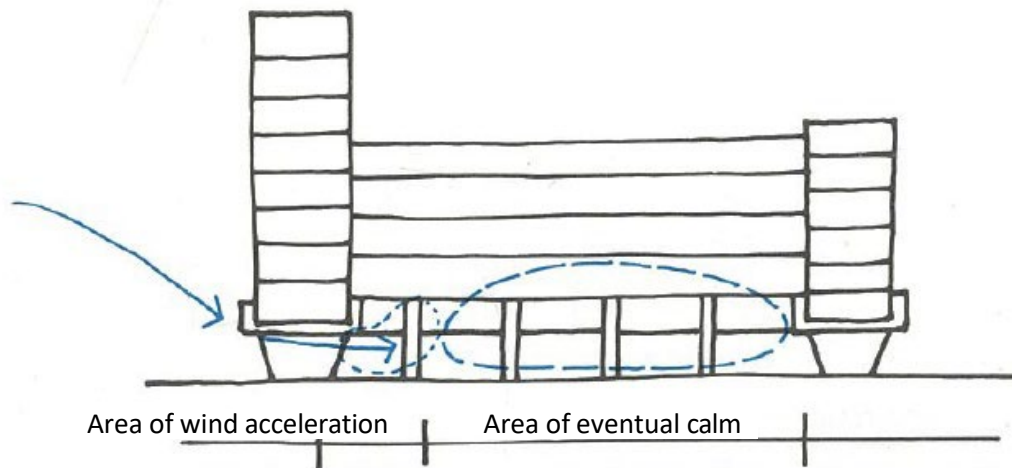
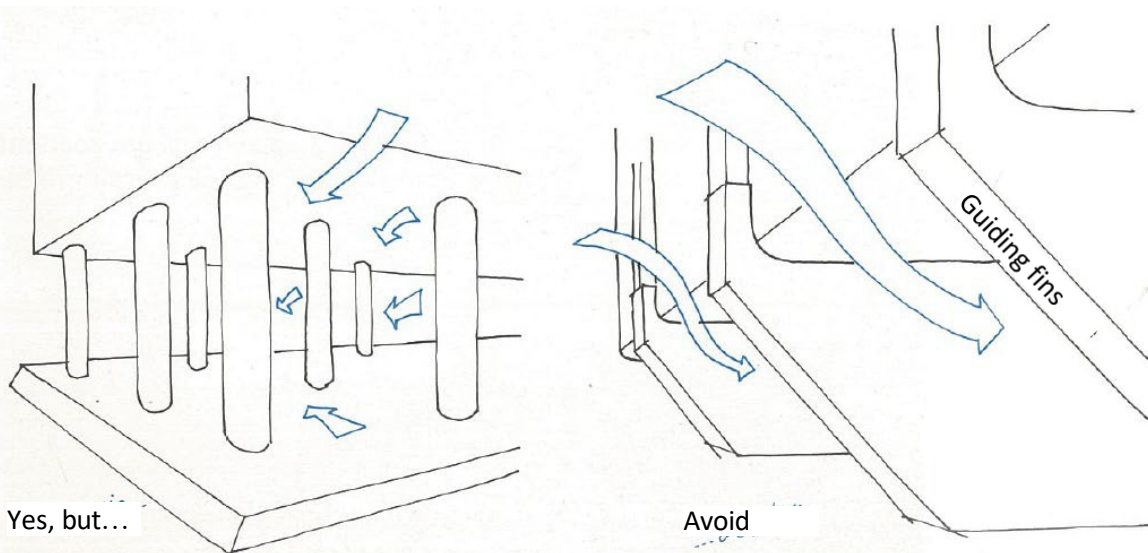


Figure 33 Pilotis can play, in some cases, the role of windbreak

Note: Courtyards surrounded by buildings on stilts can offer acceptable comfort in the courtyard, though not under the buildings themselves.

Practical advice

- Orient buildings on stilts or with "holes" aligned parallel to the wind.
- Provide the base of buildings with vegetation and solid constructed objects to diffuse the flow.
- Introduce at the level of the connecting volumes elements that produce pressure losses.
- Avoid solid-form buildings on pilotis.
- Divide the flows at the foot of buildings by increasing the porosity of the building.



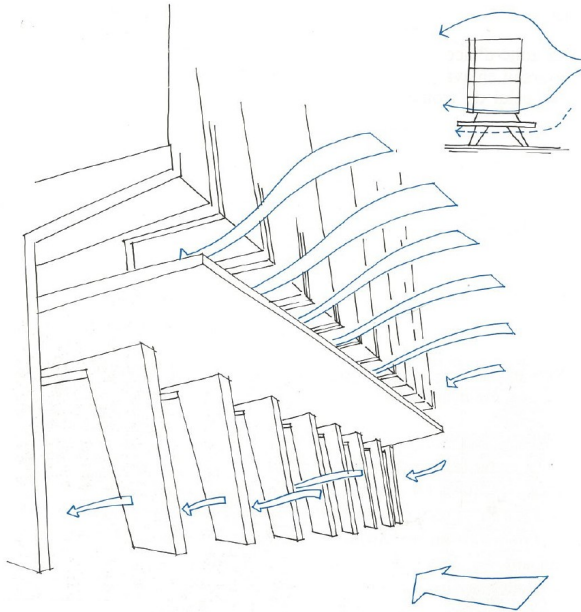


Figure 21 Pilotis (stilts) effect mitigated by a division of the flow

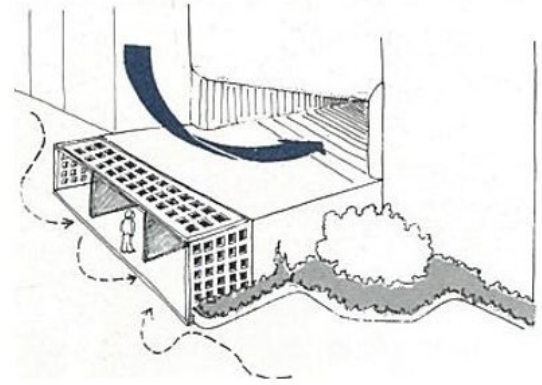


Figure 20 To be fully effective, the passage for pedestrians is separated from the air dissipation flow vertically and horizontally



Figure 22 Example from Wellington of divided flows to reduce the problems at the foot of buildings by increasing the porosity of the building - car park levels at first floor and above – with retail below



Figure 23 Example from Wellington of divided flows to reduce the problems at the foot of buildings by increasing the porosity of the building - slot through the building <1m high at first floor above retail

5.3.6 Pedestrian corridors and foyers

The designer's responsibility for adverse wind effects does not end once wind conditions in the street have been addressed. The entrances to buildings, foyers and pedestrian corridors can also be areas where there is pedestrian discomfort or even danger.

Discomfort can be experienced both inside and outside entrance doorways. There may be a high fluctuating wind pressure outside the doorway, which creates a high pressure on the door itself, and given the opportunity, generates a wind flow into the building. Wind whistles through gaps, and doors bang. There are both damage and safety risks, and there can be difficulty in operating doors and lifts. In extremely bad situations, it is not unknown for lift doors to jam because of the severe local wind pressure.

Increases in wind pressure can turn stairwells and corridors into unpleasant wind tunnels, and can disrupt heating and ventilation systems. Buildings adversely affected by wind may require three to four times more heating than unaffected buildings.

Practical advice:

Entrance-ways to building foyers and pedestrian corridors should be designed or located to avoid users experiencing adverse wind conditions. This means:

- locating them well away from the corners of buildings;
- not linking through the building so that the high pressure on the wind facing façade is linked to the suction on the rear of building, even if via wind lobbies on each façade;
- ensuring that doors can operate safely without risking jamming fingers;
- designing effective wind lobbies where the inner and outer doors are sufficiently spaced apart that one will close before the other opens – this normally means spacings closer to 10m than 3m in an office building; and
- looking to ensure the doors into a wind lobby are not directly facing each other to reduce the direct flow of wind into the building

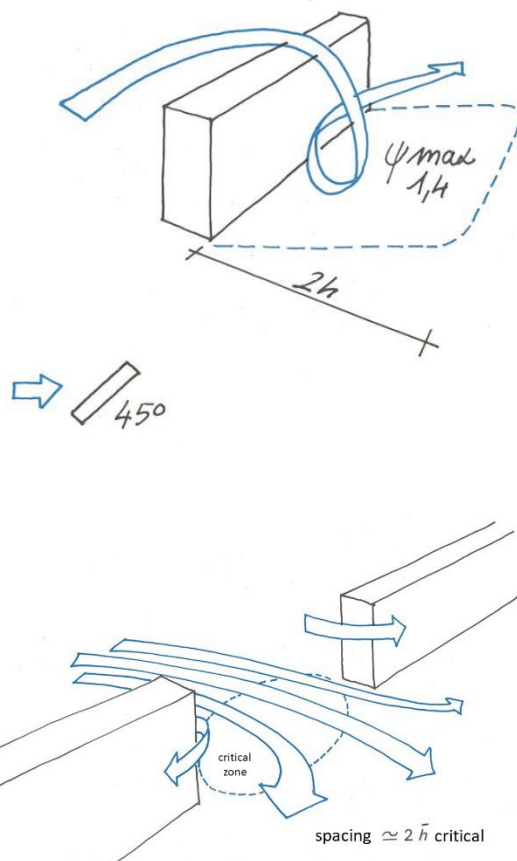
6.0 Interaction between groups of buildings and wind

It is not possible to predict what the effect of a proposed building or open space will be on wind conditions around adjacent developments without a Quantitative Wind Study. Unexpected wind patterns can and do occur. This section, like the previous section, is intended first as guidance during early design to the potential interactions of groups of building with the wind. It is intended that it is also used during the analyses in Qualitative Wind Assessments and Quantitative Wind Reports to document the likely impact of a proposed building and provide a rationale for the selection of potential remedial design interventions.

The wind effects described in section 5 all relate to the interaction of a single building with the wind. When groups of buildings are being assessed, the wind effects can be cumulative and all the buildings need to be considered.

This combined increase in wind speed may be substantially reduced if existing or subsequent buildings nearby are of suitable height to give a localised stepping-down effect. This may occur where the difference in height between the protruding building and windward adjacent buildings is less than one-third the height of the protruding building.

6.1 Low bar buildings (“row” effect)



Low, “bar”-shaped buildings which present wide unshielded faces exposed to any prevailing winds cause the wind to literally ‘trip’ over these bars. When a building or group of buildings is narrow, less than 10 storeys high, and its length is approximately eight or more times its height, and the wind is incident at roughly 45 degrees to the row then a 40 percent increase in discomfort can be expected behind the building for a distance roughly 2 times the height (h) of the building.

Where there are openings in a row, and the row is up to 8 storeys in height (and the predominant wind is angled at the row), an up to 30 percent increase in discomfort level may be experienced when the width of the opening is one to two times the height of the row.

6.1.1 Practical advice

The row effect can be reduced, or even cancelled, by adding one or several wings to the main block, thus localising the pedestrian wind level disturbances. To be effective these wings should extend away from the building by roughly 2 times the building height.

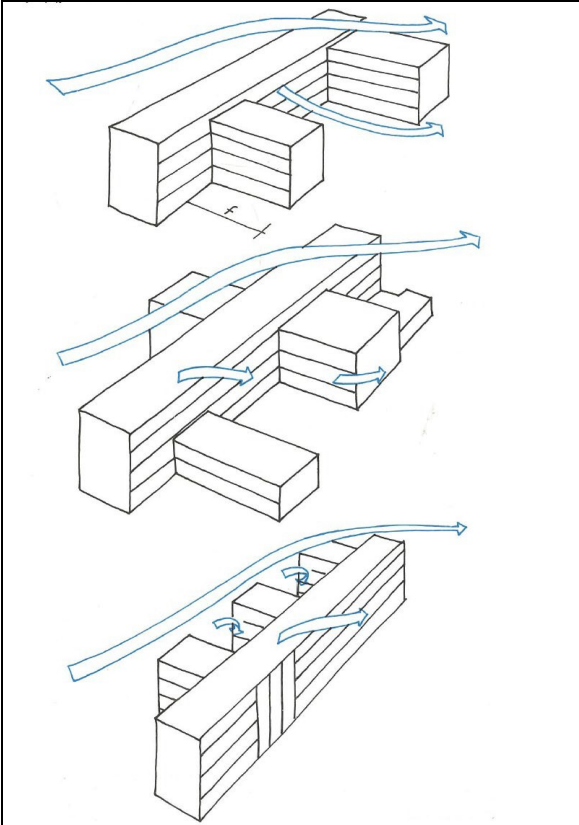
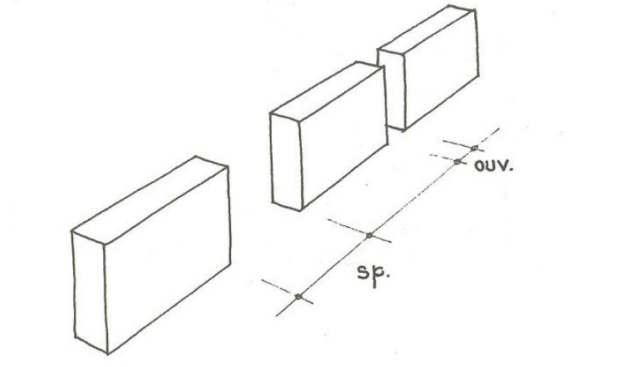
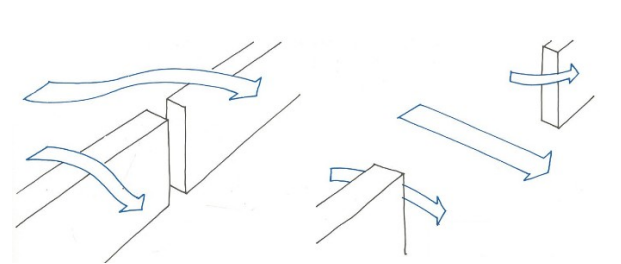


Figure 24 The flow cannot roll over the row: “overall” behaviour of the form.

The openings in a row of buildings are areas where accelerated wind flow can occur and there is a critical dimension where the wind is accelerated.



Space buildings less than their height (h) apart, or more than twice their height ($2h$) apart to avoid wind accelerating through the gaps, then porosity is such that geometrically there is no row.



6.2 Low and high buildings in combination

When wind flows over rows of buildings of a similar height, as in older parts of a town, pedestrian areas are generally sheltered; usually considerably better than if there were no buildings at all.

However, where a low building is upstream of a high building and the high building exceeds five storeys, there are likely to be major problems/increases in discomfort at ground level.

For example, downwash from a 90-100m (30-storey) high building with a wide windward face will cause a 50 percent increase in discomfort at its base when the building is on its own. There would be an 80 percent increase in discomfort if there were a low (e.g., 10-15m) building upstream of the tall building, that is spaced at a distance approximately equal to the low building's height upstream. A low 4 storey building 'tripping' the wind flow in front of a 10 storey building would lead to a wind speed increase of 50% at the base of the 10 storey building.

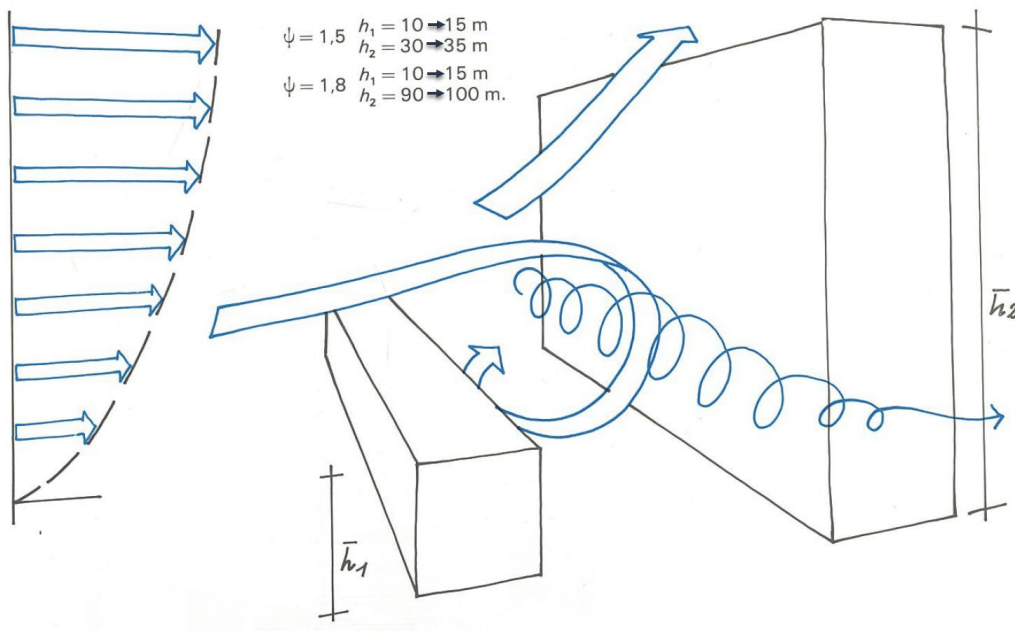


Figure 25 Accelerations due to associations of buildings of different heights: factor ψ represents how much the wind flow is accelerated: $\psi = 1.5 =$ multiply wind with no buildings by 1.5 or a 50% increase in wind

Practical advice:

- Avoid critical associations or cover the exposed area.

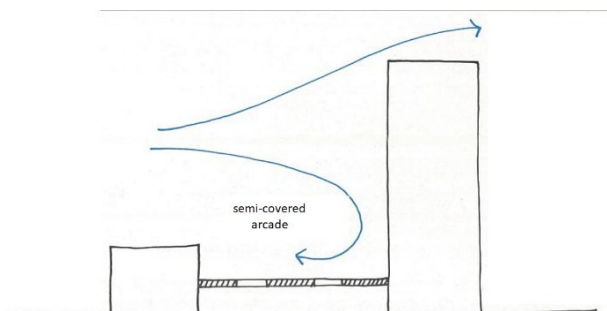


Figure 40 A potential solution to downwash is to provide a cover that diffuses the wind

6.3 Staggered buildings

Adjacent buildings may protect each other from high winds, or may make their wind environment worse. The buildings in *Figure 41* show an increased wind pressure on the unsheltered area (+) and a decreased pressure at the sheltered areas (-). Consequently, wind rushes from the high pressure point to the low pressure area. This effect is significant because of:

- the large area at ground level which is affected (the area is related to the height of the buildings – the distance between the buildings should be less than their average height for the acceleration to be significant);
- the ways that the massing/scale of the buildings and relationship to other buildings can exacerbate the adverse wind effects. Discomfort levels are wide-ranging, depending upon the scale and interrelationship of the staggered buildings and other building nearby; and
- For the phenomenon to exist the minimum average height of the buildings is approximately 15m. The effect is felt in the whole area of overlap of the buildings.

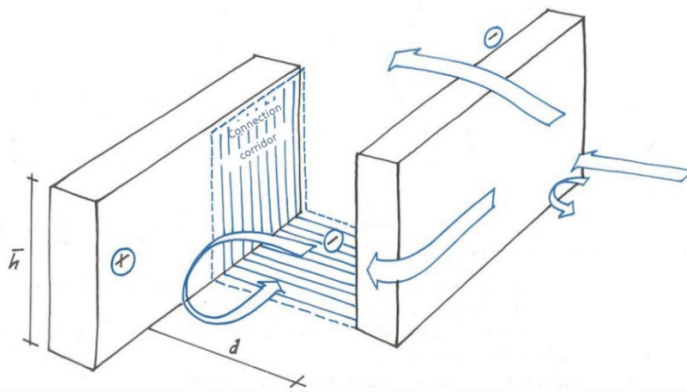


Figure 41 The anomaly affects the entire connection 'corridor'.

The staggered buildings effect, especially when associated with other phenomena, leads to unexpected changes of wind direction in city streets. This is particularly bad in terms of discomfort that is experienced.

For a 15m tall buildings, the anticipated acceleration in the overlap zone is 20 percent. For a 35m tall buildings the acceleration is between 30 and 60 percent.

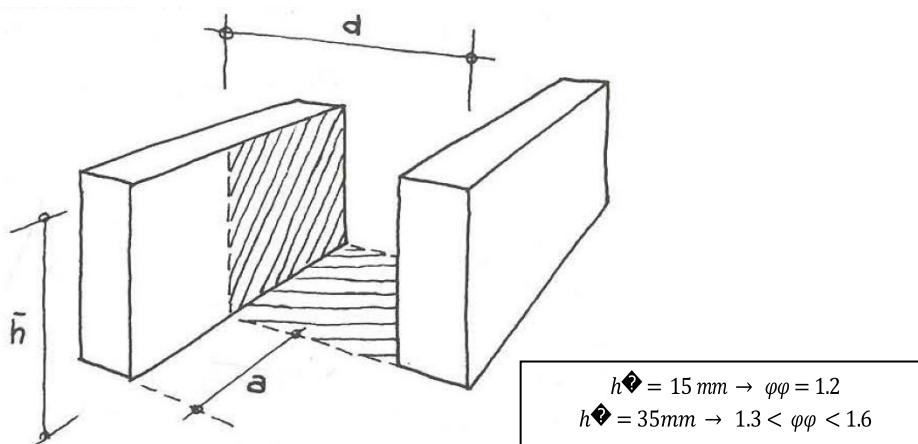


Figure 42 Quantification of the effect of height on the phenomenon

For two towers spaced relatively close together the acceleration in the overlap zone can be up to 80 percent. In this case the worst effect is when the distance apart of the towers is one quarter of the depth of the towers in the windward direction.

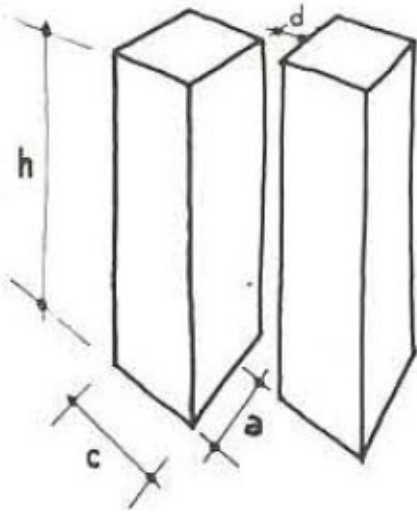
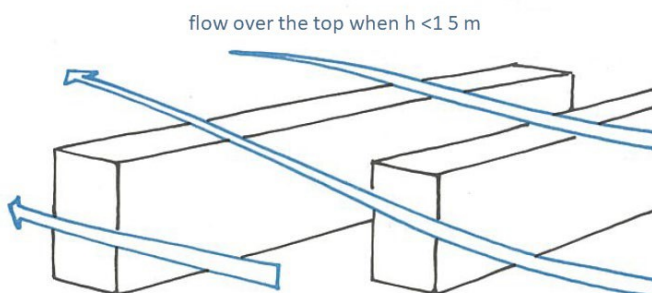


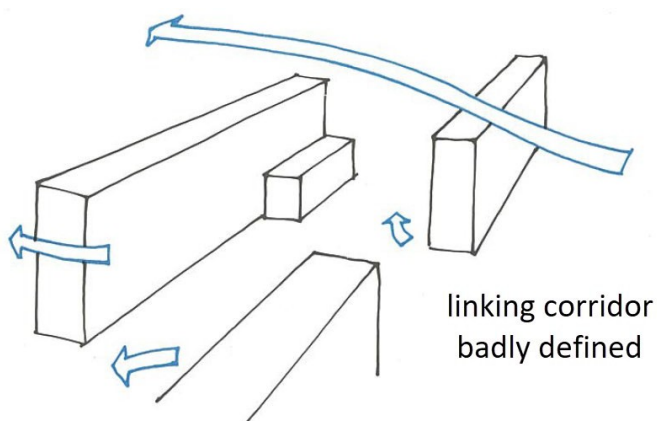
Figure 26 The worst wind accelerations in the gap between the tall towers occurs when $d \approx c/4$ then $\psi \approx 1.8$ (acceleration = 80%)

6.3.1 Practical advice:

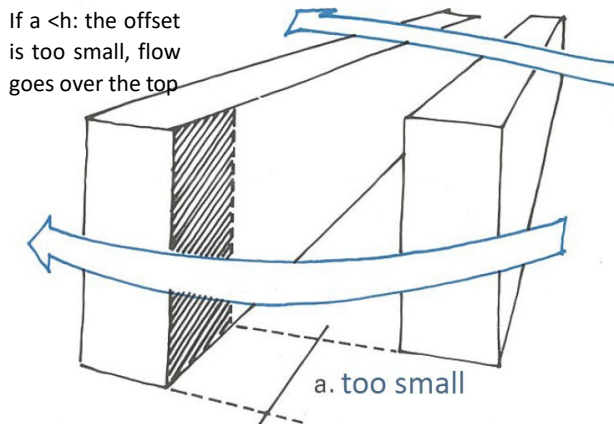
- The phenomenon does not occur if buildings are less than 15m high.



- If a link corridor is poorly defined (low porosity or flow blocking element), the phenomenon does not occur.

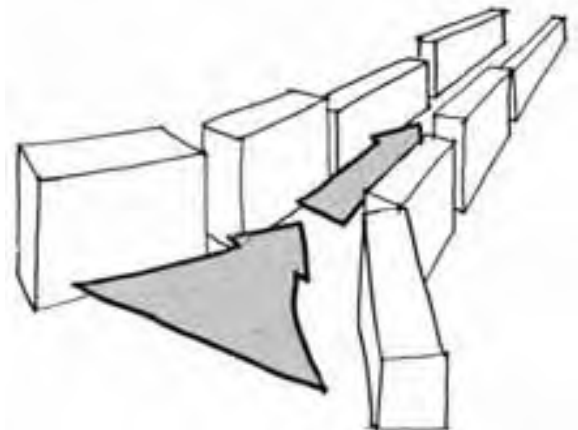


- The phenomenon does not occur if the unsheltered area of the leeward buildings is too narrow. The width of the unsheltered area must be at least the height of the building, $a \geq h$



6.4 Channel effect

A row of buildings running more or less parallel to each other forming a channel or corridor is not in itself a cause of discomfort, but it can cause discomfort when it receives some other adverse wind conditions and transmits them for the whole length of the corridor. Adverse wind effects are accentuated when the corridor is well-defined (such as there being few gaps and generally similar height buildings) and is relatively narrow (when the width between rows is less than three times the buildings' height). The channel effect can be reduced by the introduction of sharp changes in direction.



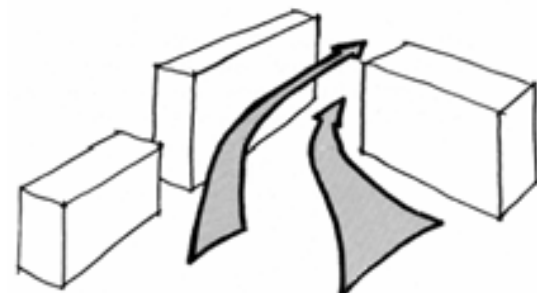
6.4.1 Practical advice:

If all the other aerodynamic anomalies such as too tall buildings, or close groupings of buildings are avoided, then there should be no concern about channelling as there should be little wind to channel.

6.5 Funnelling effect

This collector, or “bottleneck”, phenomenon is created by two structures with an opening between them. The axes of the two may make a right angle or an acute angle. The critical zone for comfort is at the neck (the narrowest section of the gap between the buildings).

Significant funnelling effects occur when the relevant buildings are more than five storeys high, more than 100 metres long, and the upstream and downstream funnels are clear of obstructions.



6.5.1 Practical advice:

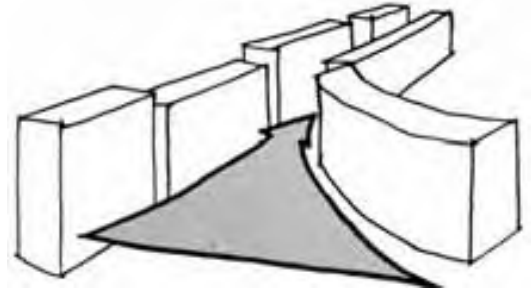
There are several “critical dimensions” to be avoided, or to be identified and mitigated in order to prevent the funnelling effect.

Discomfort is worst when the width of the opening is two to three times the mean height.

Buildings 30m high cause a 30 percent increase in discomfort and buildings 60m high cause a 60 percent increase.

There is a greater wind acceleration where the venturi effect applies. If, after a bottleneck, the rows of buildings diverge, then an aerodynamic nozzle is formed, and wind will accelerate once past the bottleneck. In this situation, building heights of about 15m storeys could cause a 100 percent increase in discomfort level.

If one or more of the buildings forming the acute angle is also curved in plan, a more aerodynamic venturi is created and the wind problem is increased.



6.6 Stepping effect

Groups of buildings which present a windward face which increases continuously in height create varying pressure zones on the lee side. Differing low-pressure zones will occur behind the different buildings. An additional wind current, often at an acute angle to the prevailing wind, will be set up between these varying low-pressure areas.

6.6.1 Practical advice:

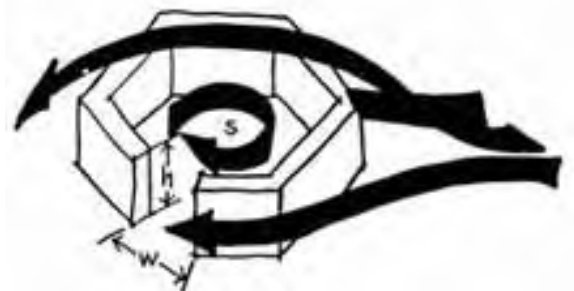
This is a situation to be aware of, and to try to avoid creating adjacent buildings with incrementally increasing or decreasing heights.



6.7 Courtyard effect

When buildings are linked together to form an open courtyard, the wind will either flow over the courtyard, or blow down into it. The following four factors have been measured in wind tunnel experiments as determining which of these two possibilities will happen:

- the surface area of the courtyard (s)
- the mean height of the buildings forming the courtyard (h)
- the position of any courtyard opening with respect to the wind direction
- the width (w) of that opening, or total width of openings (w must be less than or equal to 25 percent of the total perimeter length of the linked buildings).

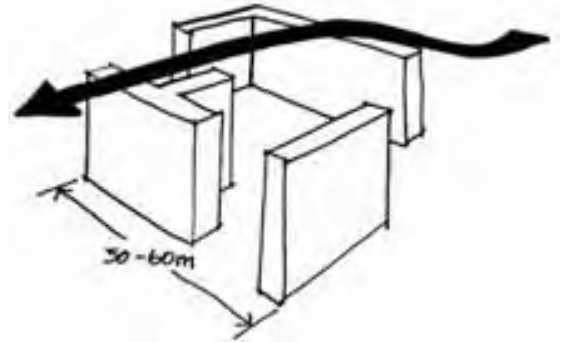


6.7.1 Practical advice:

The sheltering value of the courtyard is felt when the average building height is five to eight storeys, no matter where the position of the opening is relative to the wind direction. So long as the area/height ratio (s/h^2) is no more than 10, then the courtyard area will be relatively sheltered.

When the average height of the surrounding buildings exceeds 10 storeys, the opening relative to the wind's direction has an effect on the shelter:

- when the opening is on the leeward side and the area/height ratio (s/h^2) is less than 30, the courtyard will be sheltered
- when the opening is on the windward side to within 45 degrees of the prevailing wind direction, the air in the courtyard will be set into a circular motion. With the opening parallel to the wind the courtyard will be sheltered.



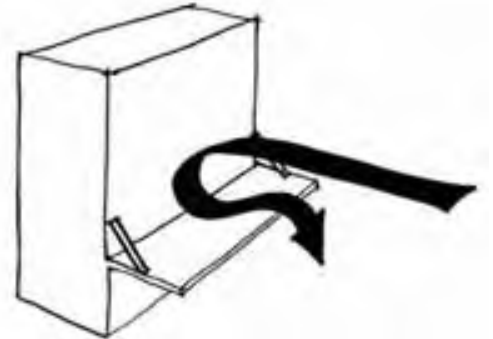
Generally, if the average height of buildings exceeds four storeys, then there will be an increase in comfort within the courtyard – even in a poorly defined courtyard system – where the system measures 50 to 60 metres across.

7.0 Architectural detailing design guidelines

Different, complex wind pressures caused by arcades, spaces under buildings or around corners can induce very rapid local wind flows, which give unpleasant, sometimes violent, wind effects.

Various features such as verandahs and channels on the outside of buildings can have a marked influence on combating adverse wind effects.

These should not be regarded as cosmetic remedies which can be subsequently applied, if necessary, to cure pedestrian-level wind problems for developments in sensitive areas. There is no adequate substitute for the careful consideration of wind at pre-design stage. This could consist of testing simple block forms in a wind tunnel.



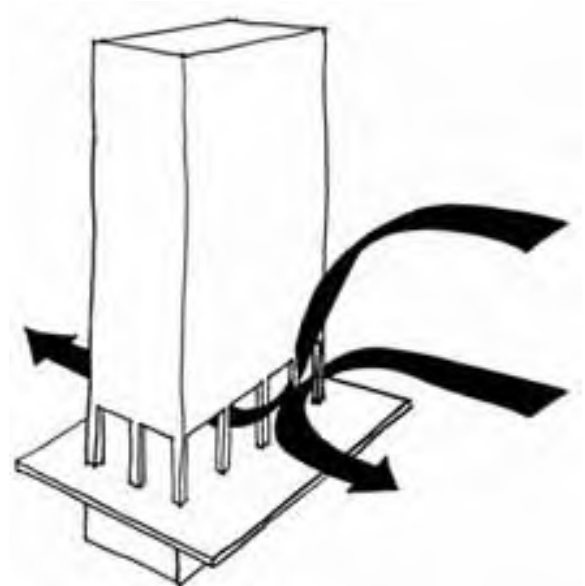
7.1 Verandahs and canopies

Verandahs are substantial structures extending from a building to roof-in adjacent airspace, whilst canopies are minor extension covers over doorways, windows or similar.

Canopies, unless extensive, do little to protect an area from high wind speeds.

- Verandahs should be used to deflect downwash flows, in effect lifting the vortex above pedestrian level.
- They can be used in conjunction with breezeways, although the associated spaces should not be open to pedestrian movement.

Verandahs are not as effective for problematic wind flows that are parallel to the building face to which they are attached. Verandahs are less effective when they are not continuous and large gaps between verandahs allow accelerated wind currents to flow through the gaps.



7.2 Awareness of existing wind mitigation

Alterations to existing buildings should not cause wind conditions to deteriorate as a consequence of removing existing mitigation measures that were specifically incorporated to ameliorate wind. Over time the utility of podiums, canopies, screens, planting and other design features described in this guide can be forgotten. It is therefore incumbent upon owners and designers to understand the wind performance of existing building before altering them.

8.0 Wind mitigation

This section describes the basic aerodynamics of isolated structures and windbreak elements, singly and in combination, that can contribute to mitigation of wind issues. A windbreak structure could be:

- a verandah;
- a canopy;
- a hedge;
- a wall; or
- some combination of these.

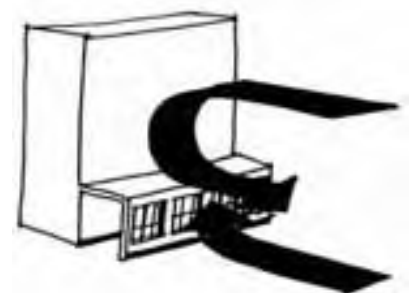
Where modification of the building itself is not feasible, it may sometimes be useful to provide localised amelioration through the addition of aerodynamic screening elements. It is never desirable to place a screening element in public spaces, or worse, in front of another building, in order to solve an issue that could have been resolved within the development. However, a recognised principle of good aerodynamic design is that the closer the screening element is to the people to be protected, the greater its likely success in reducing wind speeds. The design principles to be applied to alterations to buildings or to isolated screening elements are described in a similar format to the earlier descriptions of the impacts of buildings on wind flows.

Remedial treatment is never a reasonable substitute for the proper consideration of wind effects during the design of a project.

8.1 Structures

Where buildings prove to be windy after construction, various remedial works may substantially reduce the adverse wind effects. Two approaches may be taken:

- people can be protected by shields; or
- they may be redirected through safer areas, for example by establishing gardens and architectural features within the danger zones.



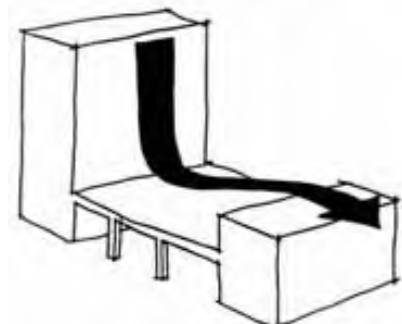
In more extreme situations, the second course is recommended.

8.1.1 Verandahs

A substantial verandah may prevent high wind speeds descending to ground level. However, care must be taken not to transfer the discomfort to another pedestrian area.

8.1.2 Enclosed walkways

The shelter effect of a verandah can be extended by the addition of a side wall.



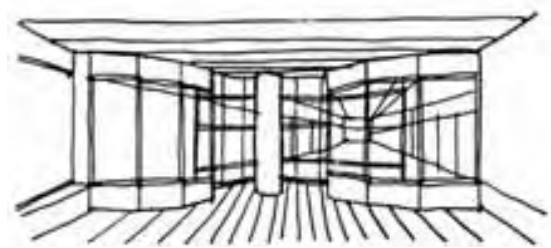
8.1.3 Roofing over the open spaces

High pedestrian-usage areas such as shopping precincts can be roofed over.

8.1.4 Pedestrian corridors and foyers

Although enclosing the walkways improves the wind conditions, there may be significant discomfort from winds induced along the entire length of the enclosed walkways.

These may be reduced by putting up screens, or eradicated by building doors at the end of the walkways. Although the addition of such doors will eliminate the wind problems in the corridor, there may well be major problems at the doors - people may have trouble passing through the doors, or the doors may jam. Electronic doors often cannot operate under large wind pressures.



8.2 Windbreaks

Definition: A windbreak can be a single item (screen for example) or a system of devices which, by its presence in the wind flow, reduces the effect of the latter (level of speed, turbulence, etc.) while within the system itself (case of several elements) only on one certain downstream distance.



Figure 44: Concrete breeze block shade screen on the Parker Palm Springs Hotel (Source: <https://bit.ly/3iGNLSA>). In another context, this could be a wind break with porosity ~50%



Figure 27 Illustration from Farm Forestry New Zealand Guide to wind shelter on farms as association of wind breaks (Source: <https://bit.ly/ShelterFarms>)

8.2.1 Independent windbreaks

Only in exceptional circumstances can individual screening elements be provided for each person. The bathing chairs of Northern Europe (Figure 46) are an idealised extension of the simple wind screening element also common at the beach in the windier parts of Europe (Figure 47). But these examples demonstrate the problem of providing individual shelter: they can often impede general pedestrian access.



Figure 28 Beach "chairs" facing the sun and away from the sea breezes, Warnemunde, North Germany



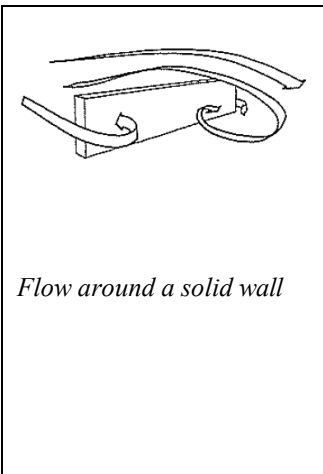
Figure 47 Example of Beach Windbreaks (Source: https://www.beaufort.be/assets/upload/stranduitbating/strandparasol_5.jpg)

8.2.2 Wind flows around windbreaks – protection factor

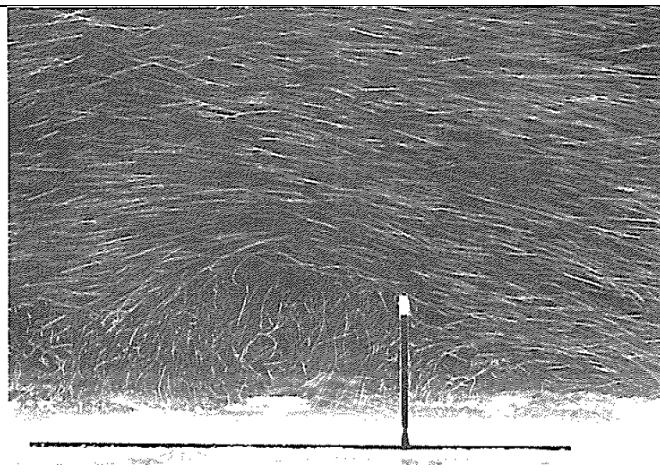
The most basic windbreak will consist of a solid obstacle (wall) or a porous obstacle (screen, hedge, palisade, etc.). The height of such walls and screens remains generally small compared to their length, and wind flows are essentially deflected above (except the ends of the wall/screen).

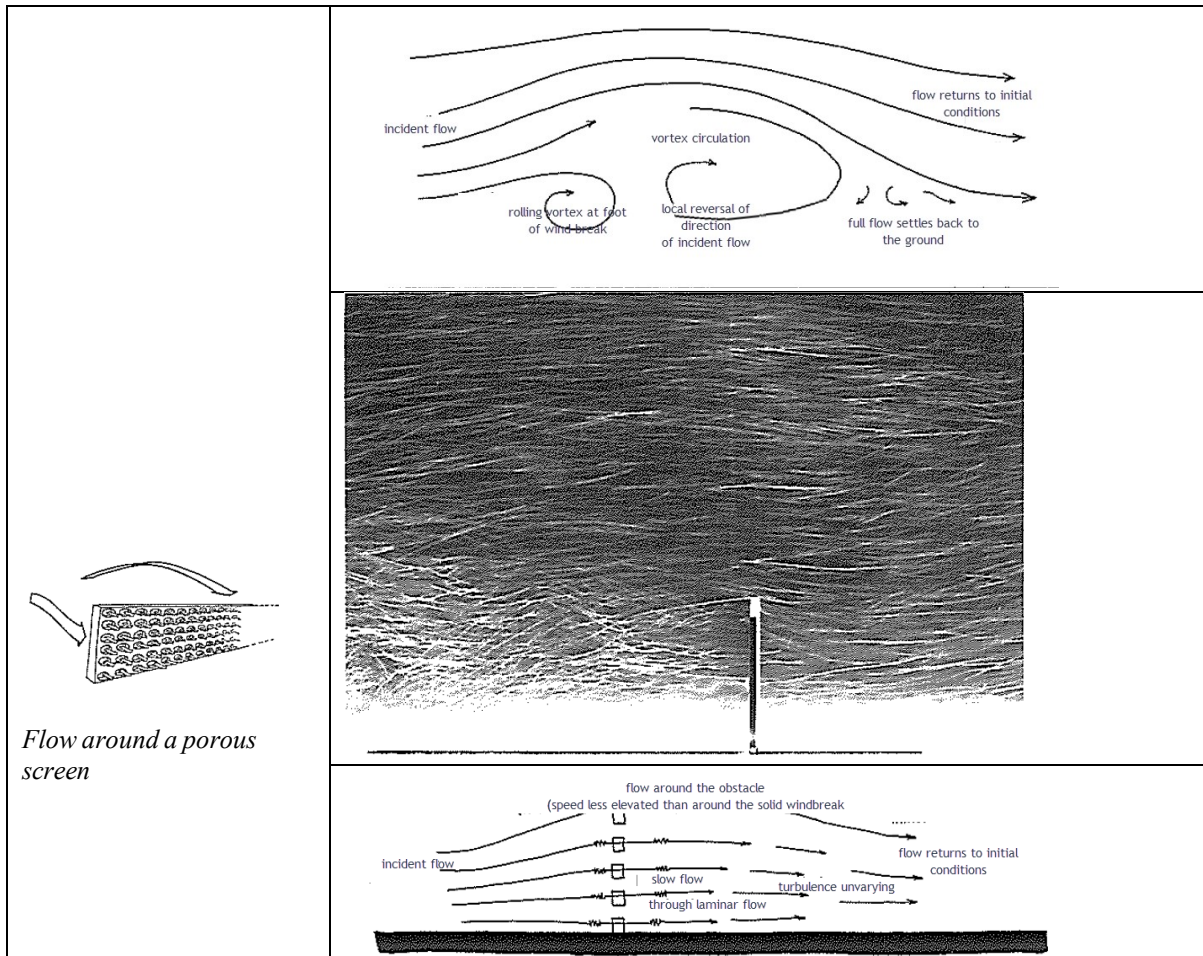
In this guide porosity is a number between 1 and zero where 0 is solid, 0.50 is equal parts open and solid, and 1 is completely open (i.e., no screen). Alternatively, the porosity may be expressed as a percentage, where 0% is solid and 100% is completely open (i.e. no screen).

If the windbreak has a large porosity, part of the incident flow passes through the windbreak, which suppresses the formation of vortex circulations downstream.



Flow around a solid wall





The images above illustrate the different wind flow around a solid wall and a porous screen. The windbreak begins to act on the flow approximately one times its height upstream of the windbreak (foot swirl and upward deflection), and above all, strongly modifies the flow downstream by forming a wake. Only at a distance some twenty times the height of the windbreak downwind has the flow recovered to be like the undisturbed upstream flow.

8.2.3 Windbreak protection factor: application to user discomfort

In order to quantify the modified area downstream of a windbreak device, and as a result be able to compare one device with another, a “protection factor” is used to describe the effectiveness of the windbreak, regardless of the speed or turbulence. This protection factor, P , is the ratio between the wind with and without the wind break.

In the following pages, the results of many wind tunnel tests are reported for winds at the height of a person (1.5 m), for a grid of points in the wake of the windbreak. Three levels of protection are reported: $P = 3$, where the wind is one third that with no windbreak; $P=2$, where the wind speed is halved; and $P=1.2$, indicating a minor improvement of 20%.

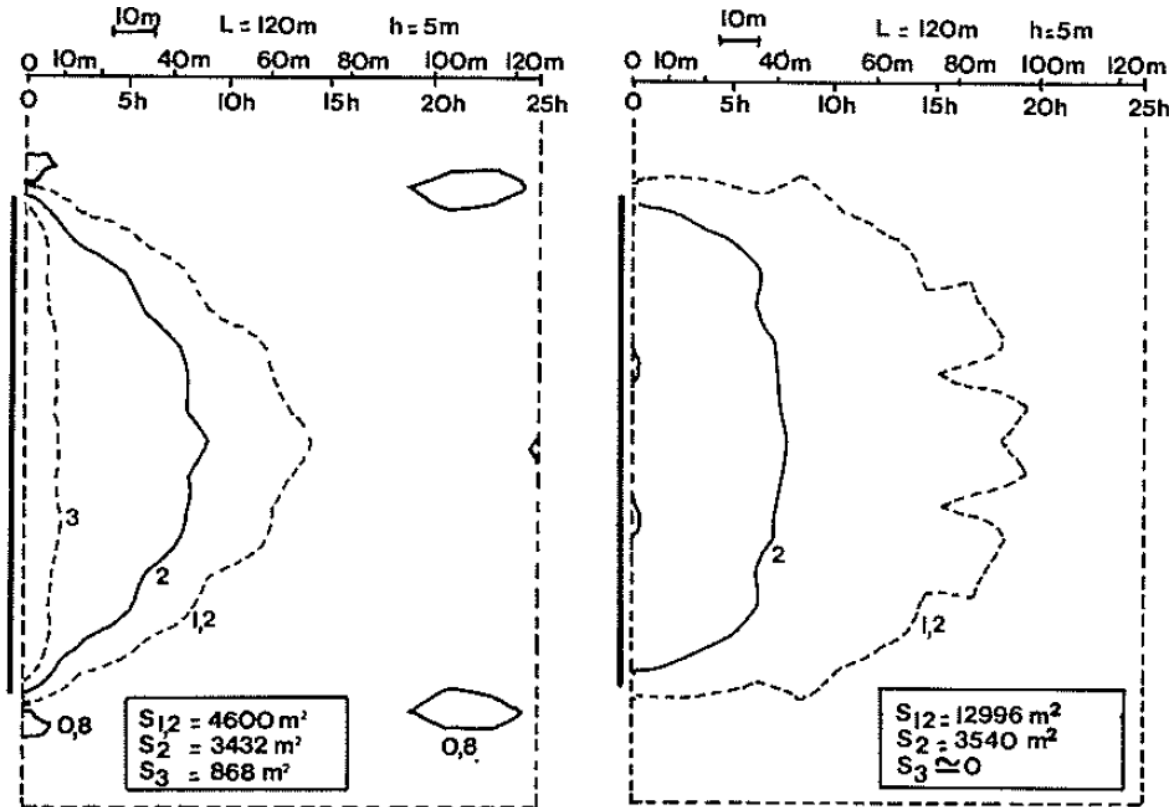


Figure 29 Isoprotection contours at a height of 1.5 m behind a solid wall (left) and a 54% porous screen (right), drawn from results of wind tunnel tests.

Figure 48 illustrates wind tunnel test results for the two windbreak visualizations on the previous page: each is of a wind shelter device 120m long and 5m high. Wind is blowing from left to right. The distance that the shelter extends from each device provides is shown by the horizontal scale at the top of the graphs which is expressed in two ways: in total metres, and in multiples of the height of the device. The porous (54% holes) screen on the right has an effect out to 20 times the height of 5m, while the solid wall has an effect only out to 15 times the height downwind. The area sheltered ($S_{1,2}$) to isoprotection level 1.2 (a 20% improvement) is almost 3 times that for the solid wall (12966m^2 compared to 4600m^2). However, the sheltered area (S_2) is almost the same for both devices inside the isoprotection level 2 line, where the wind speed is reduced to at least half of the wind with no wall. At protection level 3, where the wind behind the barrier is reduced to one third of that with no windbreak device, the solid barrier provides protection 1-2 times the height downwind for a total area of 868m^2 ; but there is no protection at this level behind the porous screen. It is also important to note that the wind accelerates around the ends of the solid wall reaching 20% more than would be experienced with no windbreak.

The action of windbreak elements, that is, how the speed (magnitude and distribution) and the turbulence will be modified by their presence, depends on a complex combination between the scale of the obstacle, the aerodynamics of the windbreak (in particular the resistance to wind), the characteristics of the incident wind and the presence of an immediate environment.

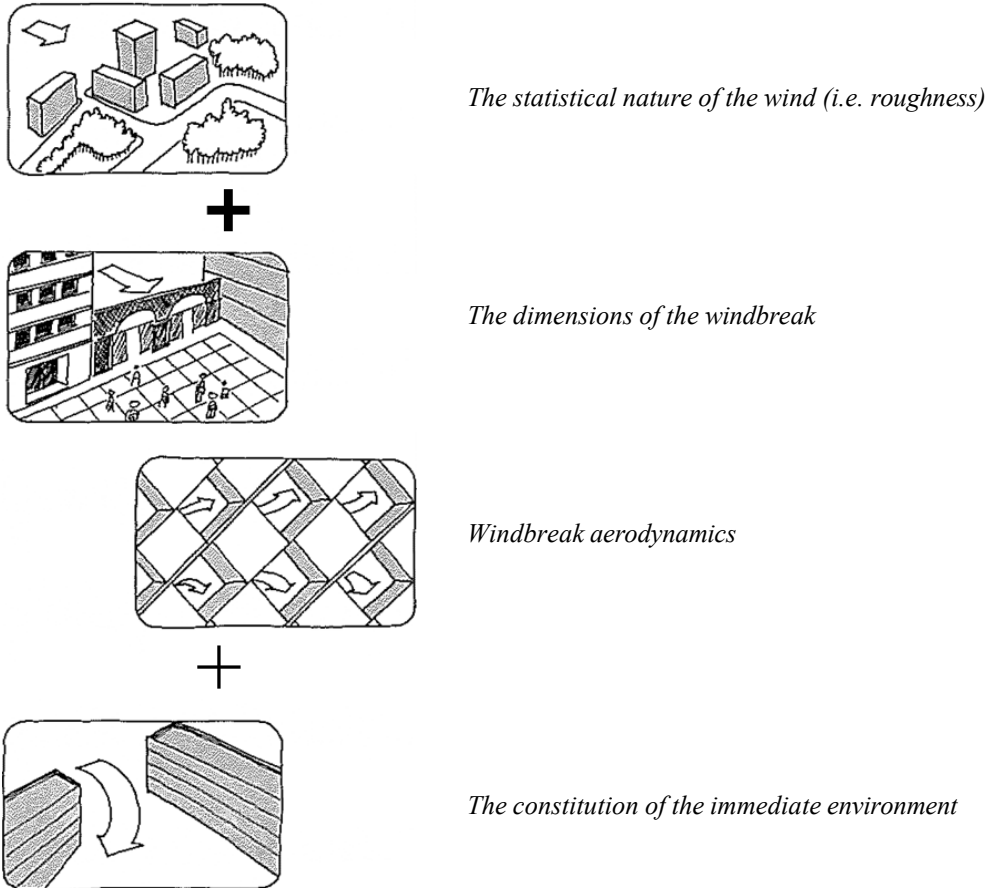


Figure 49: Elements of a windbreak function

8.3 The functions of a windbreak

Whatever the field of application (inconvenience and safety of the user or civil engineering), any protective effect will be obtained from the control of:

- 1) the speed level and its spatial variation (horizontally and vertically);
- 2) the turbulence rate and its homogeneity; and
- 3) the axis and direction of flow.

Therefore, the device can have the following functions:

- Slow down the air flows by introducing obstacles into the flow that dissipates kinetic energy. For example, the flows through orifices or increasing the friction of the ground by varying its surface roughness.
- Breakup the turbulence by reducing the dimensions of the vortices. The viscosity of the air induces a damping effect on small scale turbulence. Wire mesh or nets fulfill this role remarkably well.

- Redirect the flows to shelter "wind sensitive" areas of a building or landscape.
- Destroy strong wind flows by “three-dimensional bursting” (i.e. deflect the flow in all directions) that breaks down the coherence and concentration of the flow. Sculptures or stabiles can perfectly fulfill this function as shown on the photograph to the right showing an example on the corner of Tory Street and Cable Street.



It should be mentioned that the interventions or devices generally combine several of these functions. In addition, depending on the nature of the protection to be introduced, the aerodynamic solution to be provided and the device which results therefrom may be very different.



Figure 50 Rozenburg wind wall in Rozenburg, Netherlands, eases the passage of large cargo ships through the narrow canal. The wall blocks about 75% of the of the wind. It is 1600 meters long and is made up of 125 rectangular and cylindrical slabs, each about 25 meters tall and 18 meters wide. (Source: <https://bit.ly/2SKLeCG>)



Figure 51 Porous metal screens enabling wind hardy plants to grow beside the harbour in Wellington, New Zealand

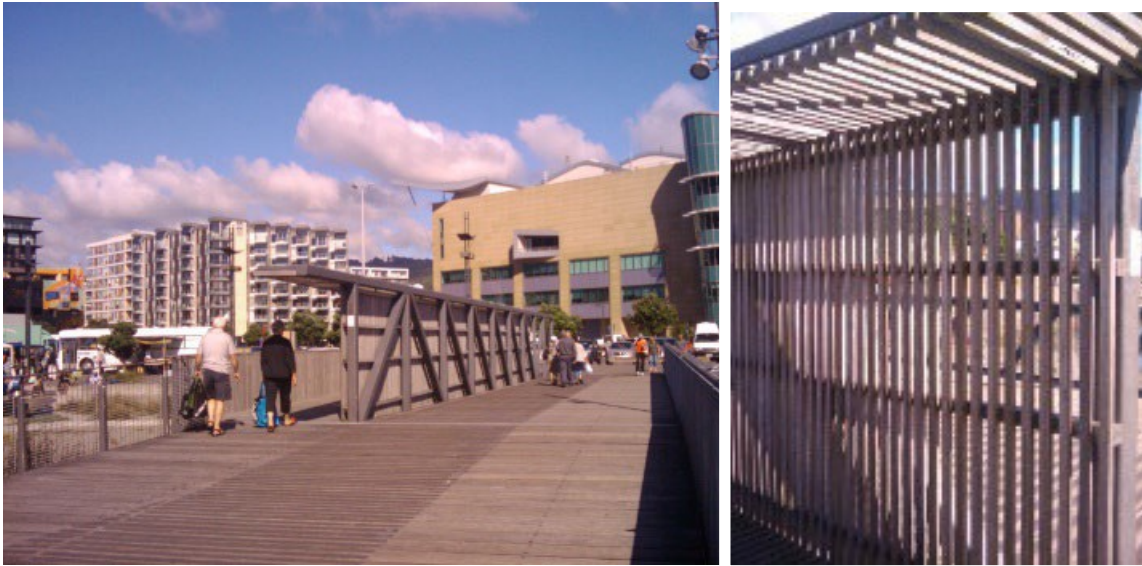


Figure 52 Porous wooden screen for pedestrian protection – harbour front Wellington, New Zealand.

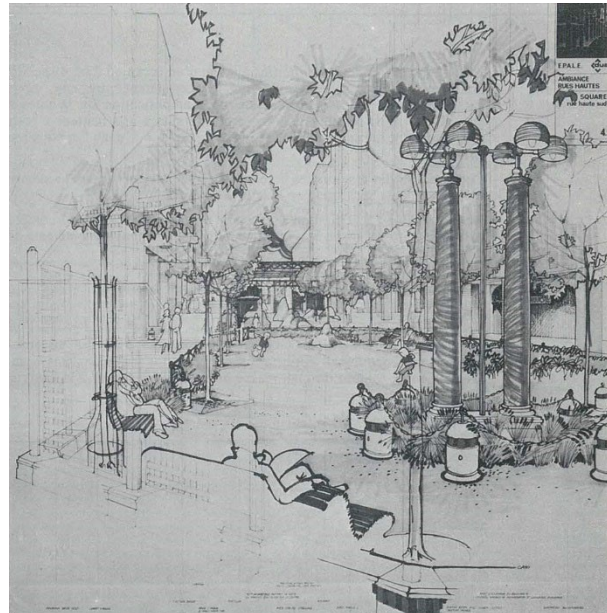


Figure 53 Shopping street development project in Lille-Est (integration of several windbreak interventions)
Architect: Canivet

8.3.1 Vegetation

The growth of trees in the area adjacent to buildings can be prevented or distorted by the wind. However, resistant vegetation can act as a porous screen and calm wind flows, whereas a solid wall or fence could create further pressure variations.

8.4 Cross-section shape of a windbreak

If the "depth" (dimension in the direction of the wind) of an obstacle is at least 30 m (a significant dimension relative to the scale of wind gusts) and the obstacle is solid, the cross-section geometry (in particular the profile of the windward face) affects the wind flow and shelter it provides. However, normally shaping the profile of a windbreak will not lead to a significant gain in protection.

8.4.1 Practical advice

The example in *Figure 54* of a “springboard slope” illustrates the minimum dimensions required to shelter an area downwind by redirecting wind flows.

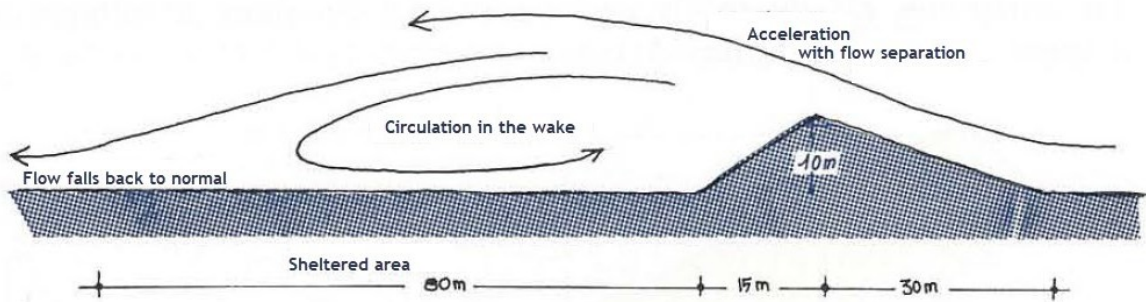


Figure 54 Diagram showing the minimum dimensions for springboard slope to redirect wind flow over an area downwind

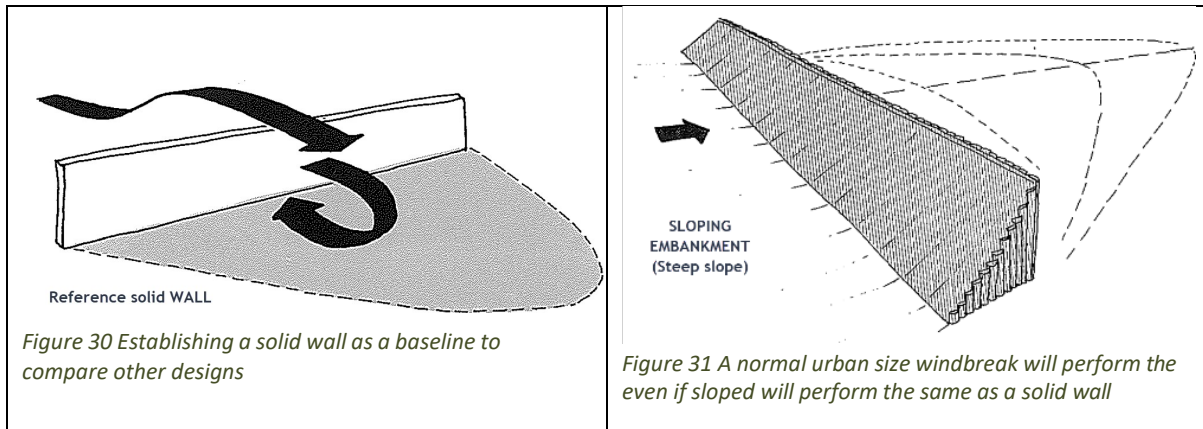


Figure 55 Protection of the boarding quay at Le Havre: concrete springboard ($h = 20\text{ m}$, length = 240m) – if this was solid, it is large enough to redirect wind flows

Urban windbreaks, screens or windbreak structures (except for vegetation, in some cases) typically have a negligible thickness compared to the dimensions wind gusts and therefore the guiding or redirection effect does not occur. Therefore, the flow crosses the windbreak without "sliding" over the obstacle and the general shape of the wind flow is practically independent of the windbreak form.

This phenomenon is even more evident when the windbreak is porous, allowing flow to pass through.

Taking the area of shelter behind a solid windbreak as a baseline, we can compare other design options.



Profiled tops or concave curvatures of the windbreak tend to reduce the protected area (Figure 58). Consequently (in this range of dimensions), the solid or porous flat windbreak is normally the best shape to adopt, since it is simple to use and the required "thickness" is small.

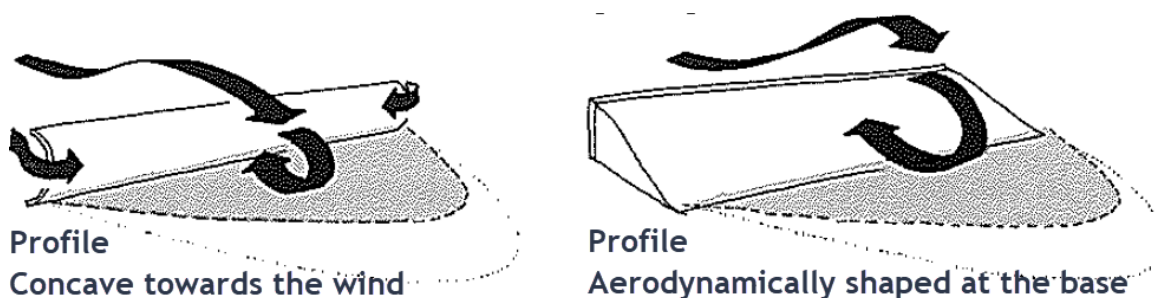


Figure 58 The shaded area behind the concave and aerodynamically shaped windbreaks have the same level of protection as the much larger area defined by the dotted line for the baseline windbreak of the same length and height.

8.5 Dimensions of a windbreak

The transverse dimensions of a windbreak (height and length) are critical to the sheltered area (in particular they affect the sheltered areas S_2 and S_3). The mechanisms for affecting the wake of the screens will be different according to the windbreak dimensions (especially the length L) compared to the transverse scales of the wind gusts. Consequently, the geometry and the area S of a given protection level P will be affected by changes in the height and length of the windbreak.

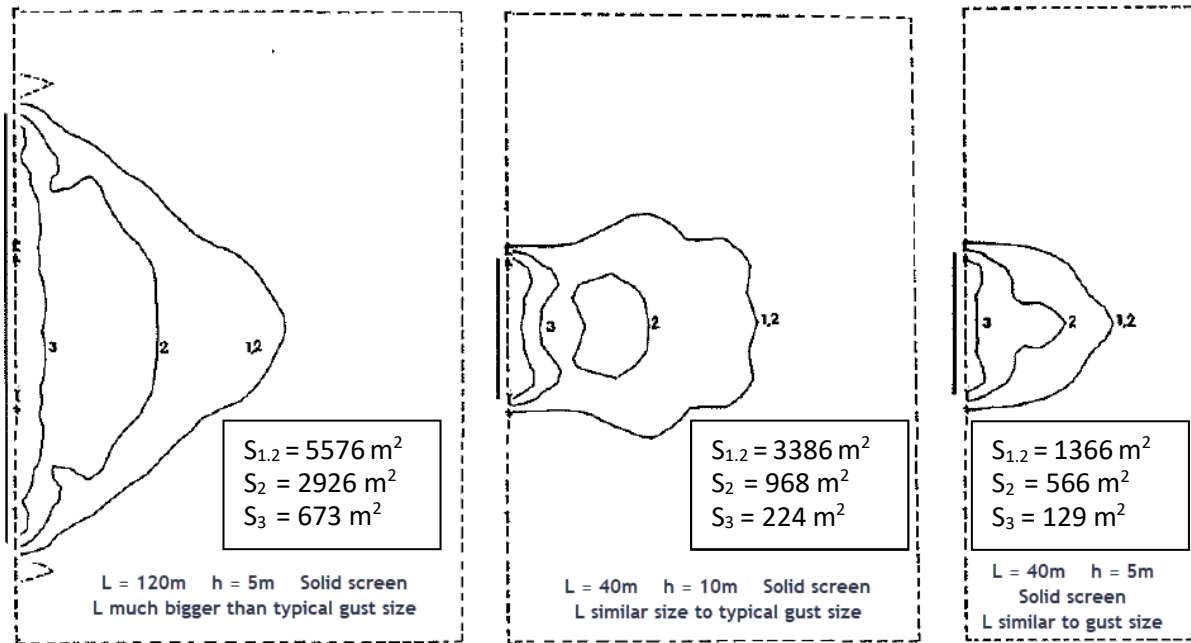
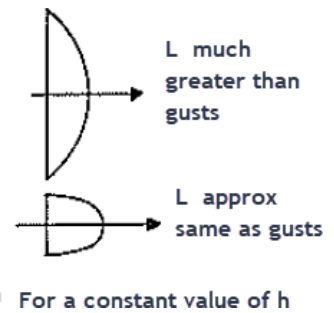


Figure 59 The protected area geometries for different lengths of a solid wall

The length of a windbreak, which (in the Gendemer study) is at least the same order as the transverse scale of the wind gusts, plays a more important role than the height, which is almost always much smaller than the vertical scale of wind gusts. The geometry of protected areas can roughly be linked to a half-ellipse with a major axis formed by the windbreak when the length (L) is much bigger than the transverse gust size; and a half-ellipse with its minor axis formed by the windbreak when the length (L) is similar in size to the transverse gust size. This difference in shelter with different height-length ratios is explained by a greater influence of the flow around the ends of the windbreak end where the transverse wind gust is similar in size to the length (L).



This difference in geometry fades as soon as the solidity of the windbreak “disappears” in front of the wind, particularly when the porosity of the screen increases.

The following estimates apply to windbreaks, in the range of length going from 20 m to 120 m, for the height range between 2.5 m and 10 m and for screens whose porosity is less than 50%:

- The area S_3 , where the wind speed is one third of the incident wind, is proportional to $L^{1.5}$
- The area S_2 , where the wind speed is halved, is proportional to $L^{1.3} * h^{0.7}$
- The area $S_{1,2}$, where the wind speed reduces by 20%, is proportional to $L * h^{0.6}$

Given the influence of the porosity, the immediate wake area S_3 where a high level of shelter occurs is not significantly dependent on the height of the windbreak. In the case of a solid wall where its length L equals the transverse gust size, the area S_3 is proportional to the wall height, h.

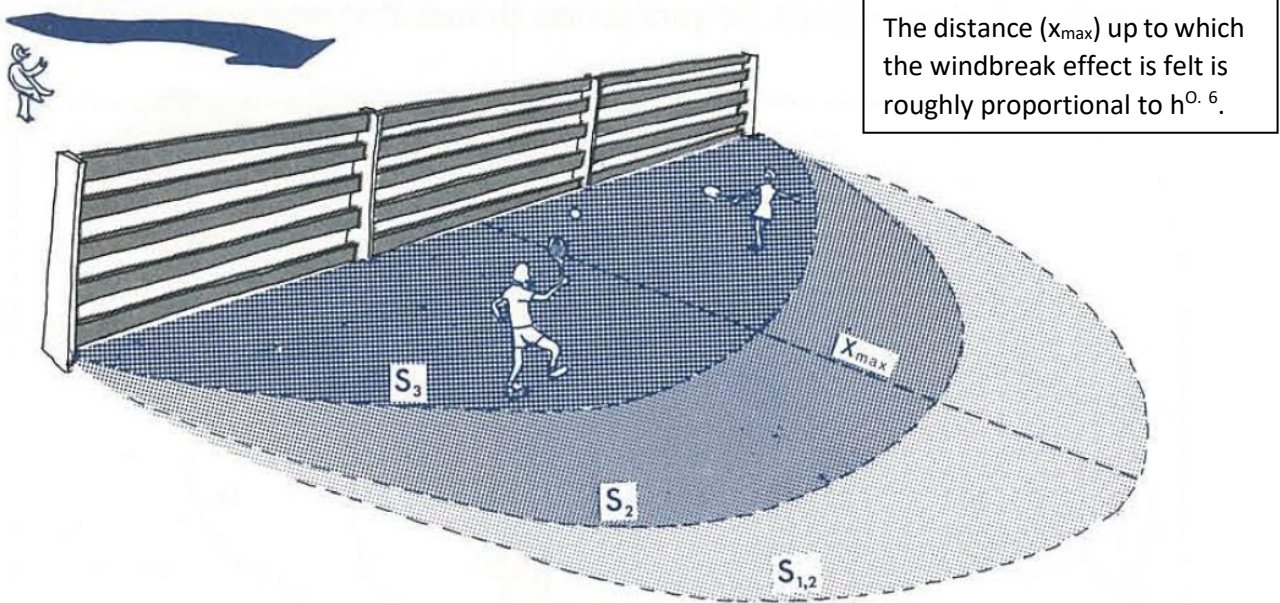
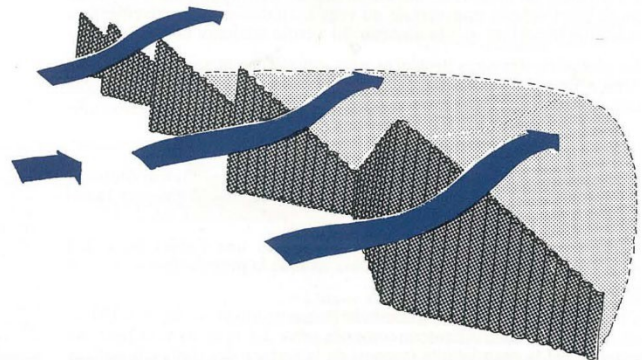


Figure 60: Areas of protection downstream of a wind break

From a practical point of view, keeping in mind the importance of height and length on the protective effect, the efficiency of a solid flat wall can be improved by varying its height and planform layout in a zig-zag fashion, as illustrated. This geometry introduces a three-dimensional wind mixing/dispersion, and provides better protection in the wake.



Protected areas (S) are increased compared to a solid wall with dimensions $h = 5$ and $L = 120$ m by about 10% for zig-zag height between $3.5 \text{ m} < h < 6.5 \text{ m}$ and planform steps spaced approximately $5 \text{ m} < l < 20 \text{ m}$.

8.6 Permeability of a thin flat windbreak

The geometric porosity used to characterize the permeability of windbreaks is defined as:

$$\Phi = \frac{\text{area of holes}}{\text{total area}}$$

The geometric porosity Φ does not fully describe the characteristics of windbreaks, in that two windbreaks of the same porosity may affect the air flow which passes through them differently depending on the dimensions of the holes, their shape (nozzle) and the type of materials used (different internal roughness for example). Likewise, plants or hedges that look solid to the eye will produce a wake that is very different from a solid wall.

Aerodynamically, it becomes necessary to introduce the concepts of pressure drop or force drag, which can be measured in a wind tunnel, but are very difficult to apply in practice. Given practical constraints (type of materials, aesthetics, etc.) the simple notion of geometric porosity is used to describe windbreaks here after.

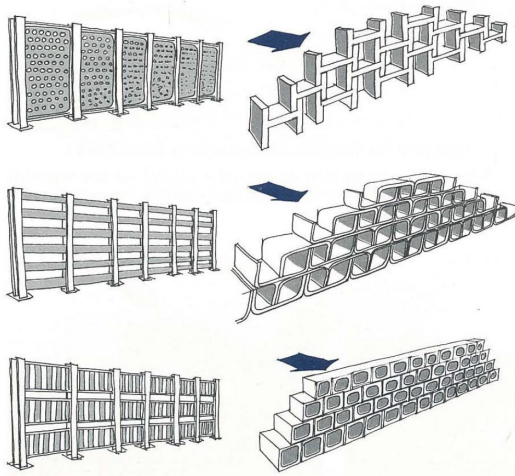


Figure 61 Examples of permeable screens (variable geometric porosity)

The porosity of a screen introduces another variable in the protective effect of a windbreak (with reference to a solid wall).

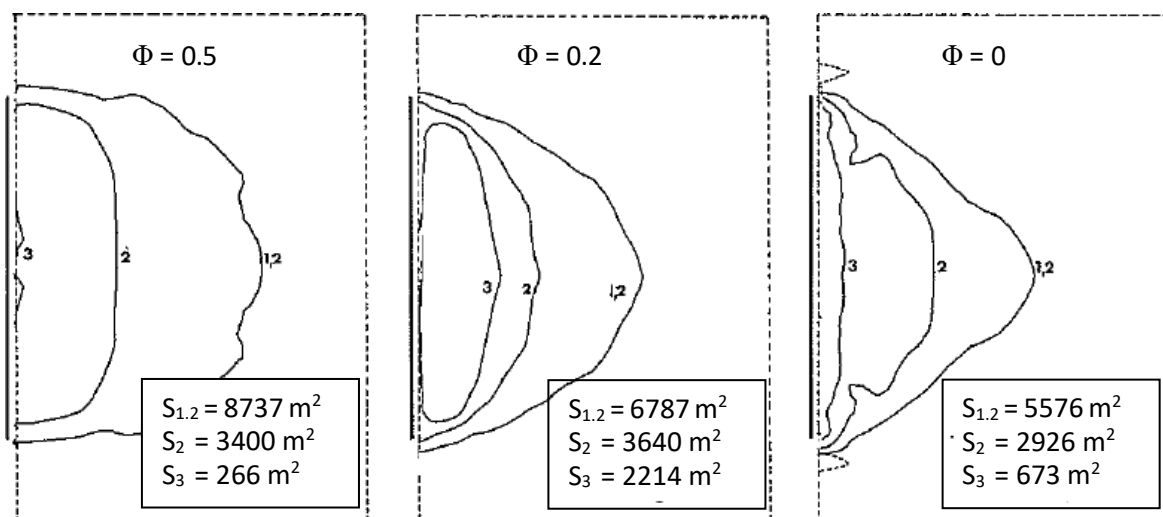


Figure 62 Protected areas (S) behind porous screens in an open country wind profile ($h = 5$ m and $L = 120$ m) (reference: solid wall $\Phi = 0$)

We can quantify the shelter by adjusting ‘porosity’ as follows:

- If you are looking for a moderate protective effect over the greatest possible area (as measured by the 20% improvement Protection Factor of 1.2) the optimal geometric porosity is approximately $\Phi = 0.5$ (e.g. large areas of crops protected somewhat).
- For better protection (sheltered areas corresponding to either Protection Factor S_2 or S_3), the optimal geometric porosity (leading to a maximum protected area) is $\Phi = 0.25$.
- When the porosity $\Phi = 0.7$ high protection areas no longer exist (S_3 is essentially zero).
- In the case of screens with a non-uniform porosity distribution, the permeability at the bottom of the screen directly affects the level of protection in the near wake (from 0 to 10 times the height h downwind).

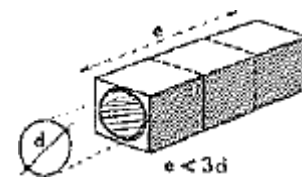
- Placing the porosity only in the lower third of the windbreak wall achieves similar sheltered area in the wake for Protection Factor S_2 and $S_{1,2}$, but removes the highest level of protection S_3 (see *Figure 63*).
- Distributing the porosity unevenly with larger gaps at the bottom of a screen gives more ventilation of the wake at the bottom. This asymmetry always produces a gain in the area of the wake sheltered at level $S_{1,2}$ compared to uniformly distributed porosity for the same average geometric porosity. The flip-side is that the areas protected at levels S_3 and S_2 are smaller (*Figure 64*).
- Distributing the porosity unevenly with smaller gaps at the bottom of a screen produces a systematic reduction of the area $S_{1,2}$ compared to a screen with uniformly distributed porosity.

Applying a variable distribution of geometric porosity in practice requires an aerodynamic “finesse”, making it prudent in most cases to use a homogeneous distribution.

8.6.1 Practicalities of the concept of porosity

The notion of geometric porosity is unambiguous for thin screens such as perforated sheet, nets, wire mesh, etc. It is advisable, however, to ensure the holes have a diameter greater than a few millimeters.

- For materials of a given thickness, additional dissipation occurs inside the orifice so the effective size of the holes is reduced. The porosity must not consist of too many small holes/gaps or the porosity will depend more on the thickness of the material. In general, the definition of geometric porosity will keep its physical meaning as long as the thickness of the material remains less than 3 times the diameter of the hole/gap.
- In the case of a thick structure where the orifices have a depth greater than 6 times the diameter of the hole, the effective porosity is 60% of the geometric porosity.
- For a given overall porosity, the distribution of the orifices must be as homogeneous as possible. For user comfort, it is advisable to choose the diameter of the orifices in the range 2 cm to 15 cm, with the limits on thickness already mentioned.
- Specialist advice will be needed to determine the effective porosity of holes, where the axis of the hole is not horizontal.



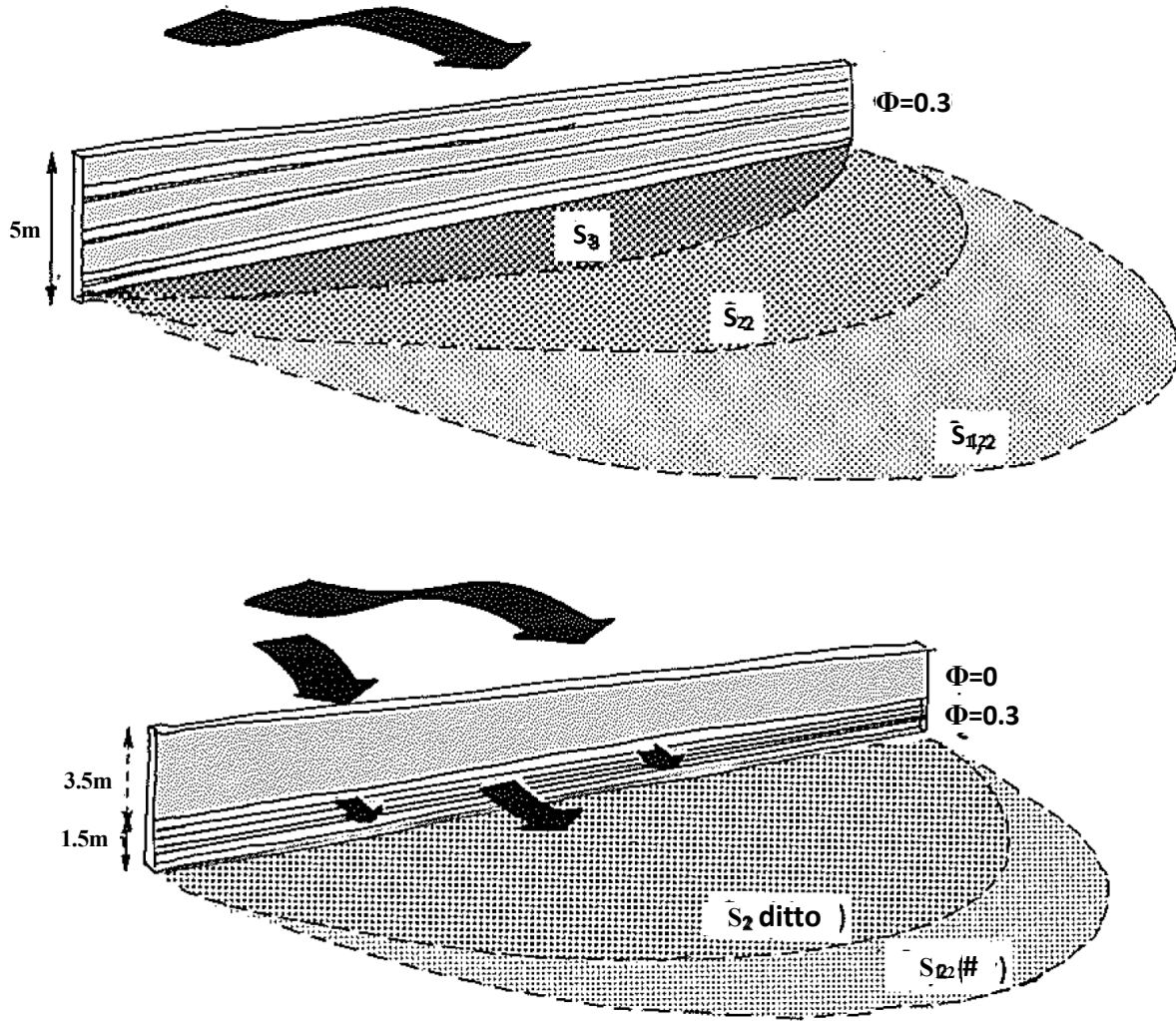


Figure 63 Placing the porosity at the base of a wall, rather than distributed homogeneously removes the Protection Factor 3 shelter, but retains a similar area sheltered at Protection Factor 2, and 1.2

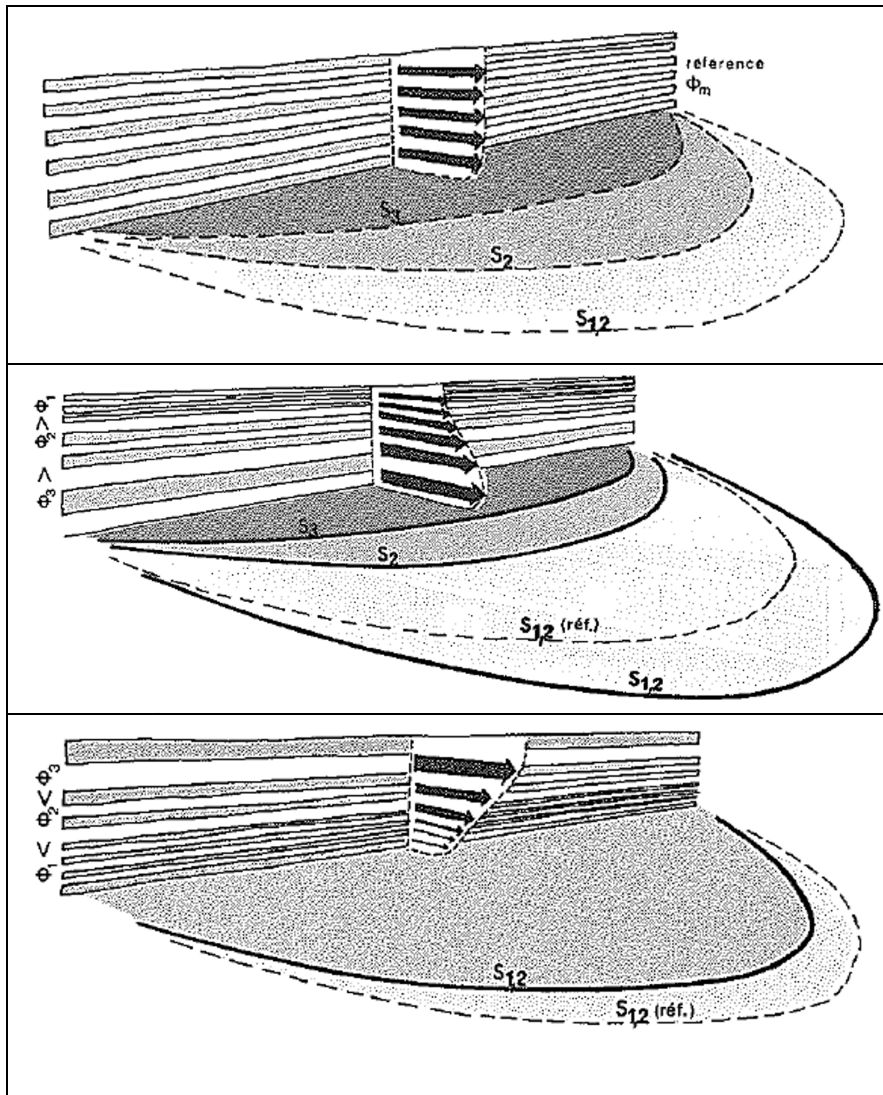


Figure 64 Asymmetrical distribution of porosity affects the area sheltered in a complex manner

8.7 Treatment of the ends of windbreaks

The strong horizontal variation in speed (horizontal speed gradient) at the end of the screens associated with the increased speed of the flow around the corners (more important as the porosity reduces) are particularly uncomfortable and also produce two downstream corner eddies that locally reduce part of the protective effect.

The following treatments are possible:

8.7.1 Practical advice for solid windbreaks

Careful design of solid windbreaks, which at their centre can provide a reduction of wind speed by a factor of 3, can be improved by modifying the flow around their ends where the accelerations are worst.

- A stairway end configuration gives protection identical to that obtained with a solid windbreak, of equal length with an abrupt end discontinuity. At the same time, the strong horizontal gradient of speed disappears as well as increased speed around the corner.

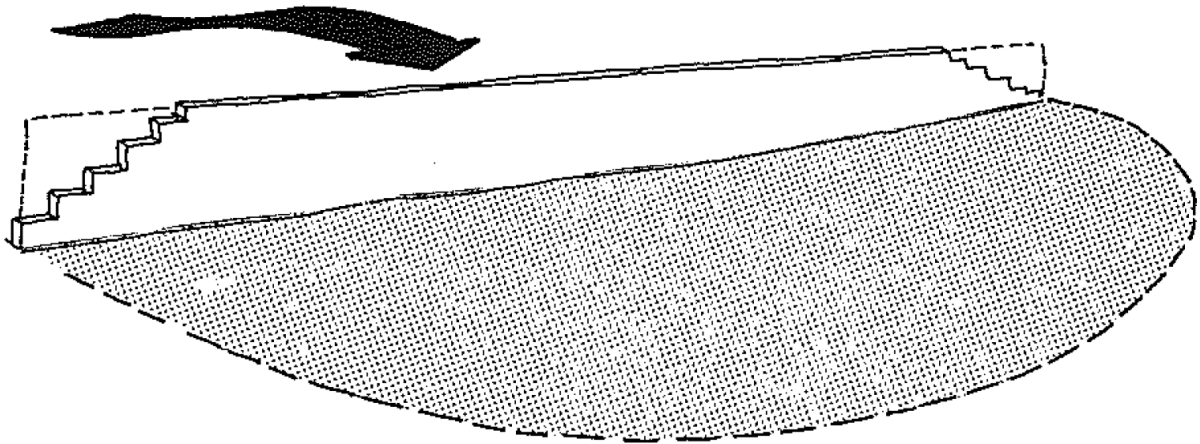


Figure 65 Identical areas of protection at all levels for the two windbreak geometries

- Increasing the porosity gradually over the last 10m meters before the end (e.g. $\Phi = 0.2$ to 0.5) eliminates the corner/end anomaly and produces an overall increase in areas $S_{1,2}$, S_2 and S_3 of the order of 25%.

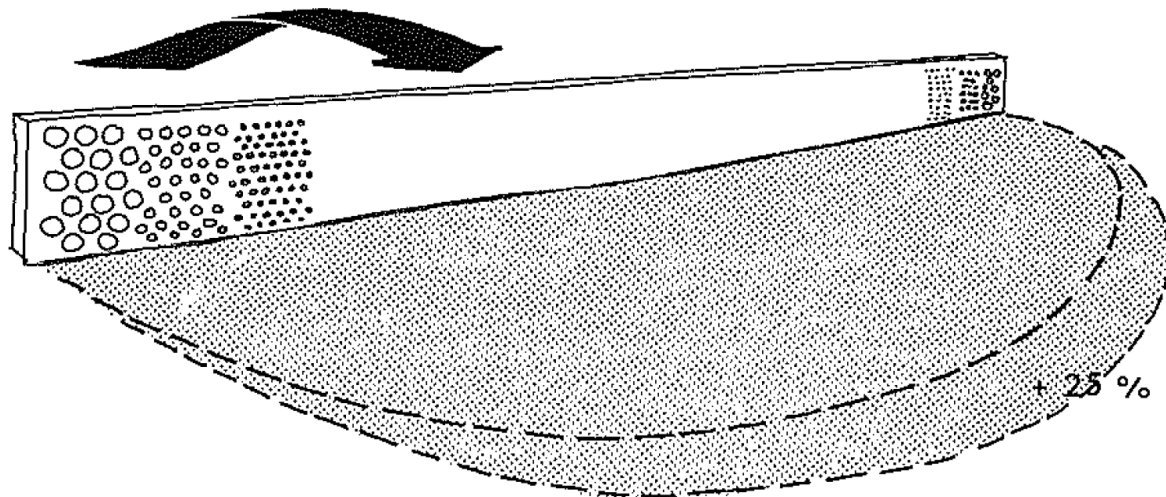


Figure 32 25% Increase in area of protection at all levels compared to a solid screen of the same dimensions

8.7.2 Practical advice for porous windbreaks

Porous screens can also be detailed to improve their functionality.

- For a screen of porosity $\Phi > 0.20$, the end effects no longer exist.
- For screens where porosity is $\Phi \geq 0.20$, adding two porous “cheeks” ($\Phi = 0.2$, about 10m long) at right angles to the screen, reduces the corner anomaly and induces a significant gain in the area protected, producing an increase of 25% in $S_{1,2}$, 15% on S_2 and 25% on S_3 .

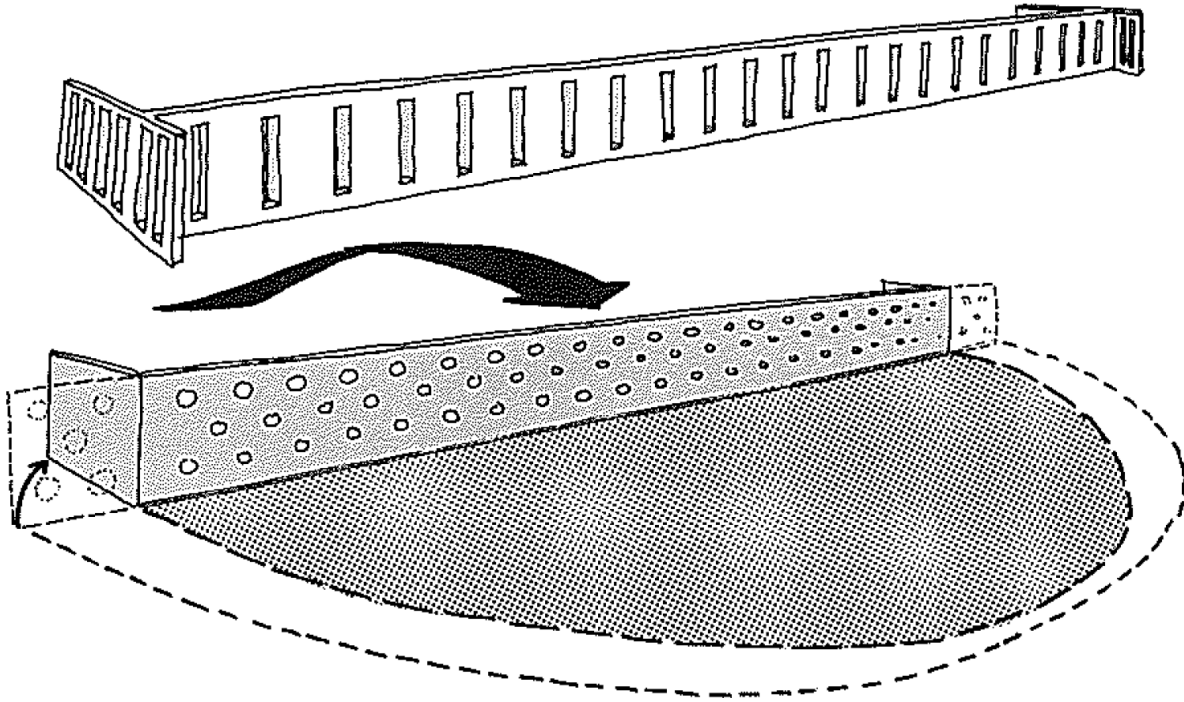


Figure 33 On an equal line, the protection is lower with both cheeks

The use of porous cheeks in the case of solid wall leads to identical gains at all levels of protection on the areas protected and eliminates the corner anomaly.

The addition of solid cheeks for porous screens improves the protected areas by approximately 10 to 15% but reinforces the corner anomaly at the ends.

For an equal linear length and for a permeability $\Phi = 0.2$, a screen with two 10m ‘cheeks’ has a worse area protected than a screen that does not have cheeks.

In practice, it is advisable to eliminate the discontinuity at either end of a screen by using combinations of stepped ends or increasing porosity. This will eliminate the corner anomaly. In addition, for permeability screens $\Phi \leq 0.2$, the addition of permeable elements aligned with the wind direction systematically improves the protective effect.

Landscaping and vegetation can also be used to treat the ends of a screen.

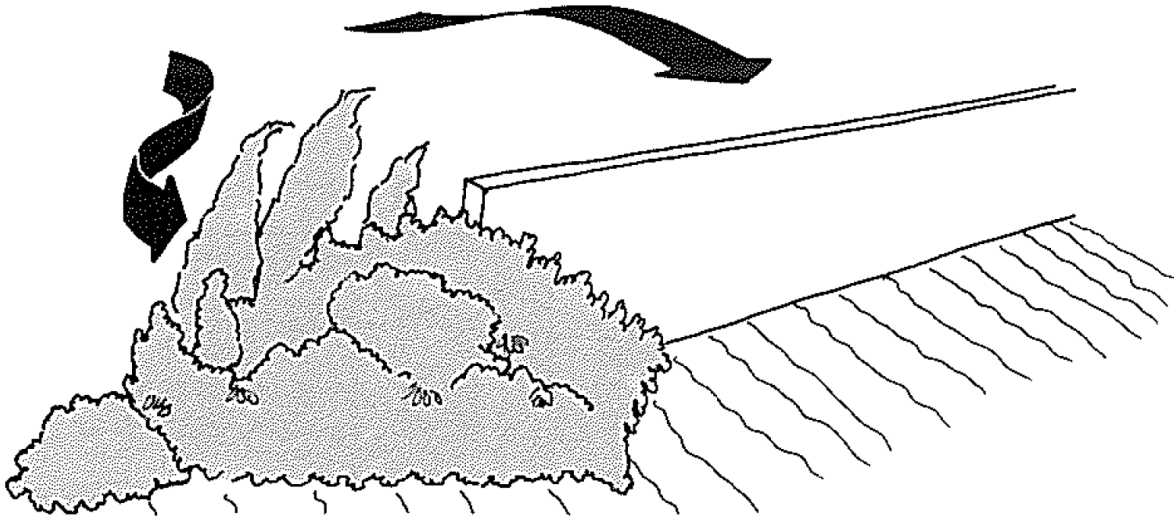


Figure 34 If the plants can grow in the extreme winds at the ends of solid windbreaks, they can provide the necessary porous transition to improve the overall function of the windbreak

8.8 Examples of combinations of aerodynamic elements

8.8.1 Springboard with windbreak on top

When the dimensions are sufficiently large (height 10 to 15 m, windward slope 3/1 and leeward slope 2/1), the springboard effect can work.

If we compare the protection behind a springboard 10 m high with a ridge whose crest is sawtooth (height between 8 and 12 m) with a distance between the peaks of 30 to 40m and with partial obstruction (about 50%) in the hollow parts at the top (windbreak of $\Phi = 0.5$ for example), there is a gain in the area (S_2) of protection where the wind speed is halved of more than 50%.

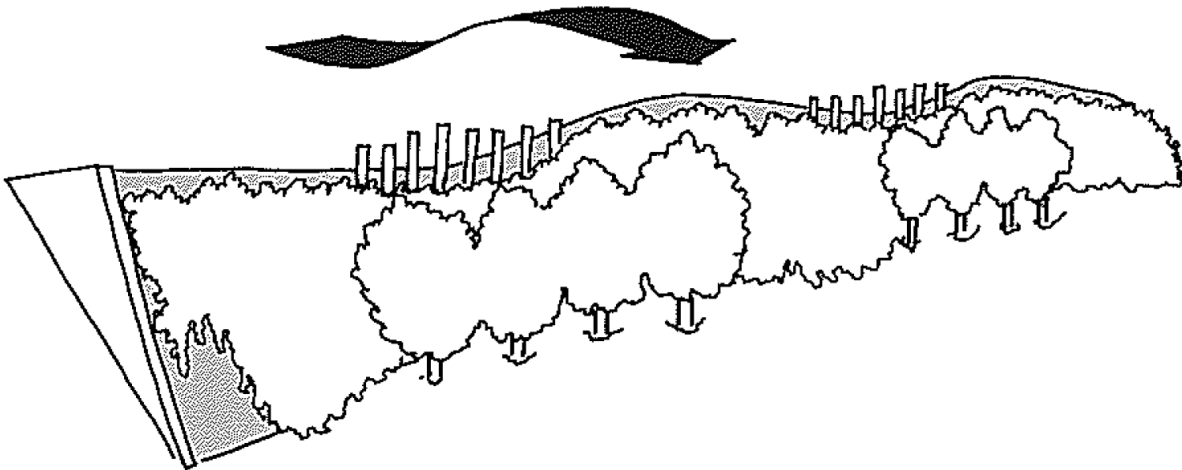


Figure 69 The area where the windspeed is halved is doubled by comparison with a simple springboard shape

This embankment architecture combines a major springboard effect and an auxiliary dissipation effect: the three-dimensional flow past the ridge (pyramid) creates accelerated flow that is dissipated by the partial obstructions. In practice, these obstructions can be created with piles, logs, rockeries and vegetation and should always be placed slightly downwind of the ridge.

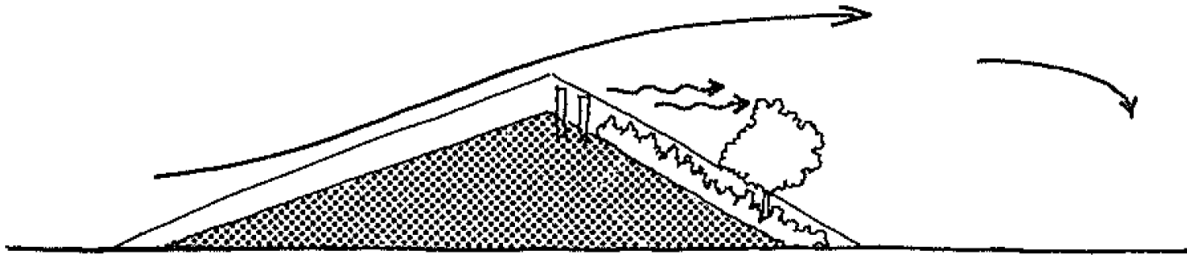


Figure 70 Wind redirection "springboard" with landscape elements that double the area of protection

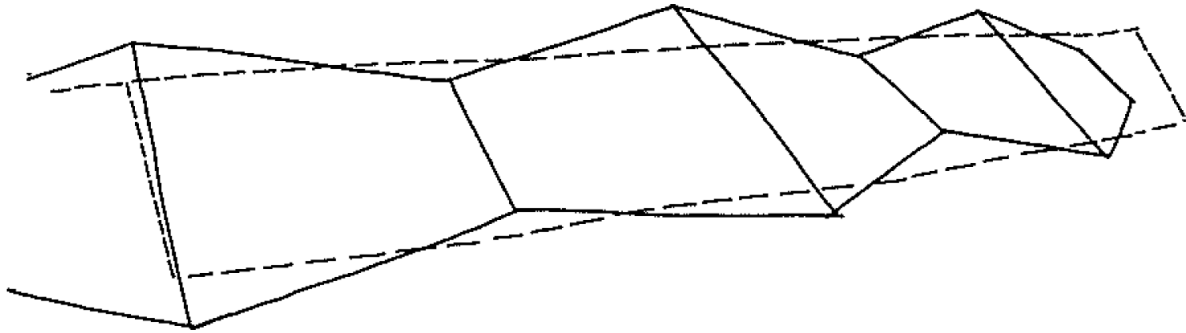


Figure 71 The crest step must be less than 40 m if it is to be "seen" by the wind.

8.9 Aerodynamic efficacy of planted windbreaks

Geometric porosity has been shown to have a preponderant role in the protective effect of windbreaks. For planted windbreaks, the porosity is a function of:

- The flexibility of the branches, the orientation of the foliage, etc. (this will vary with the wind speed and as a result vary from one moment to another).
- Depending on the foliage of a shrub or hedge, the "filtering" provided by the leaves may not be equivalent.
- The amount of foliage at ground level, or not, which may result in a large porosity at the base due to open spaces between the trunks at the base of the foliage.
- The season will affect the protection behind deciduous foliage, which will become non-existent.

When the effective geometric porosity of trees and hedges is the same as the artificial screens previously discussed, planted trees and hedges provide equal shelter to that behind the artificial screens. Therefore, the parameters that describe the protection downstream of trees and hedges are:

- the linear (Length, L and height, h) dimensions of "the planted obstacle";
- the "visual porosity" (visual percentage of the screen that is open); and
- the overall form.

The porosity of a hedge depends on the nature of the plant, its composition and thickness. Although the "visual porosity" is somewhat subjective and schematic, it allows the protective effect against the wind to be classified simply:

- Hedges whose percentage of "visual porosity" is practically zero behave like an artificial thin screen of the same dimension (L, h) and a geometric porosity $\Phi = 0.2$. The protected areas

are the same. This is the typical case of conifers (pruned or not) in a dense strip (tight planting), such as cedar and cypress.

- Protection over a greater distance can be achieved with underplanting. For example, a cypress windbreak with clumps of plants at their base (creepers for example).
- Hedges with a visual porosity of approximately $1/3$ (forms can be identified through the planted obstacle), will give protection identical to that of a thin screen of geometric porosity $\Phi = 0.5$.
- Hedges whose visual porosity is of the order of 50 to 60% provide much less shelter downstream. It is estimated that such a hedge has the protective efficiency of a thin screen of geometric porosity $\Phi = 0.7$. For example, the majority of deciduous hedges in winter have this porosity.
- For visual porosity greater than $\Phi = 0.7$, hedges provide no wind protection.

A problem of windbreaks that comprise a screen of trees is that the base, around the tree-trunks can be completely open. In the case of dense leafy foliage, ventilation at the base may even introduce an acceleration of the flow over the entire height of the open trunk and which extends over a distance of 1 to 2 times the height downwind. For example, a curtain of maples (high trunk) or pines will have zero protection at their bases.

If the windbreak is formed from large trees that emerge from dense bush or a natural hedge, the homogeneity of the texture is consistent and the classifications based on visual permeability will be relevant. Thus, for an estimated "average" height and visual porosity, it will be possible to estimate the protection level ($S_{1.2}$, S_2 et S_3) behind a screen of trees of length L .

Sticks or saplings of cherry trees, chestnut trees and oaks (visual porosity $1/3$ and corresponding geometric porosity $\Phi = 0.5$) have a protective effect over a larger area (particularly in the distant wake) than more opaque foliage such as leafy curtains of ash and elms or cypress (zero visual permeability and corresponding geometric porosity $\Phi = 0.2$). On the other hand, the more opaque foliage offer a higher level of protection in their immediate wake.

8.9.1 Wooded strips (thickness about 20 m)

The protection provided by woody strips whose base, or undergrowth, is trimmed (bush, regrowth, etc.) and thickness of at least 15 m constitutes an almost ideal windbreak:

Close to the wooded strip, in the wake there are very high levels of protection ($P = 2$ and 3) while far downstream a protection effect ($P = 1.2$) persists (beyond 200 m for a wooded area about 10 m thick). Furthermore, wooded strips of thickness greater than 20 m have a similar behaviour.

The minimum area of protection downstream of a wooded strip (natural constitution of oaks, beeches, etc., with coppice on the ground) or of a forest (height h , and length L) can be estimated by using a porosity of $\Phi = 0.25$ in the calculation for the level of protection $P = 2$, and a porosity of corresponding to $\Phi = 0.5$ for a level of protection $P = 1.2$.

Finally, an open space with a radius of 100 m surrounded by a wooded crown (height $h = 10$ m and a thickness of 20 m) will have a level of protection higher than $P = 2$ over its whole area.

8.9.2 Composition of the planted screen – practical aerodynamic advice

A wide variety of plants, shrubs and trees can be used to create windbreaks. Climate and practical constraints of implementation will be the preponderant parameters, provided the following aerodynamic principles are respected:

- Planted screens should be of homogeneous texture. Depending on the species used, a variety of vegetation will be necessary, especially around the foot of shrubs or trees.
- Optimal porosity corresponds to visual porosity that is zero (high immediate protection, widely used in the vicinity of dwellings) or low (larger-scale protection, used in rural areas). Consequently, the foliage of planted screens should be dense. This density is a function of the species but also of the thickness which is planted and the relative arrangement of the plants (staggered, parallel rows). A landscaper or the horticultural engineer will be able to advise the best choices for specific applications.
- Optimal efficiency is obtained, as in the case of artificial screens, for an orthogonal incidence. During the establishment of the plants, a wind shield will have to be installed to allow the growth of the plant screen. This shield can be made, for example, of mounding of earth, rockeries or robust creeping plants.
- The combinations of planted screens works in a similar way to artificial screens:
 - Courtyards formed by a planted hedges (height about 3 m) of 10 m radius will provide a particularly protected microclimate protection $P = 3$ (for all wind directions).
 - The combination of two hedges with a visual porosity of 0.3 and spaced approximately one times their height apart leads to a protective effect greater than what could be obtained with a single hedge (of the same height) that is opaque to the eye.

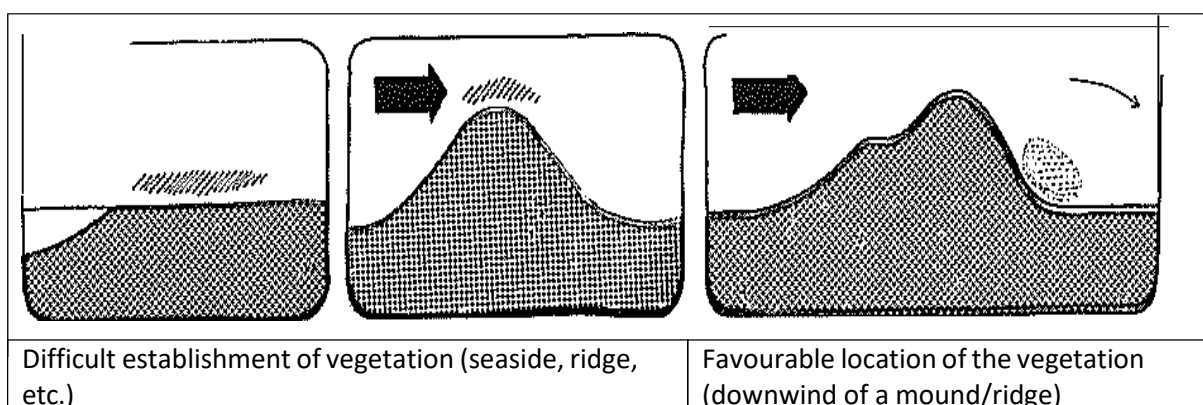
8.9.3 Implementation constraints

The fundamental difficulty using plants to control microclimatic environments are their living nature! It is therefore advisable to ensure some precautions are taken when plants are used as a "windbreak".

To guarantee effective protection against the wind, it will be necessary to ensure the proper conditions for the growth of the plant screen. The richness of the soil and water supply will determine the success of planted windbreaks, and the maintenance and upkeep of the plants will have to be taken into account.

Planted windbreaks require the following factors (including the aerodynamic concepts in the preceding paragraphs) to be considered:

- the degree of exposure to the wind: depending on the climatic characteristics of the region or the topography of the site, strong exposure by the sea or on a crest makes the development of the vegetation difficult, while in the open area at the foot of a hill the atmosphere will be much more favourable.



- In exposed areas, it will be necessary to use resistant species, and appropriate use of the plant that develops naturally on the site will help to solve the problem.
- By the sea, the aggression of salt spray complicates the implementation. In some cases, it will be necessary to provide for washing the leaves to remove some of the corrosion of the salt.

Mesh screens can be used temporarily or permanently (*Figure 72*) to ensure good growth until tress mature.

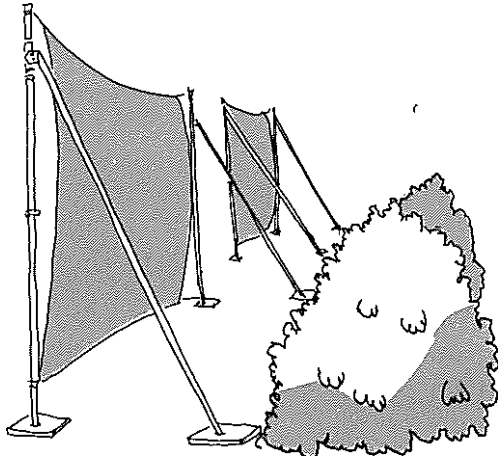


Figure 72 Use of stretched mesh as temporary windbreaks



Figure 73 Wind hardy plants with permanent metal mesh screens enabling them to grow (somewhat) in salt spray zone at the seaside

In the area exposed to the wind, the morphology of the vegetation can dictate the choice of species and contribute to the chances of development of the planted screen.

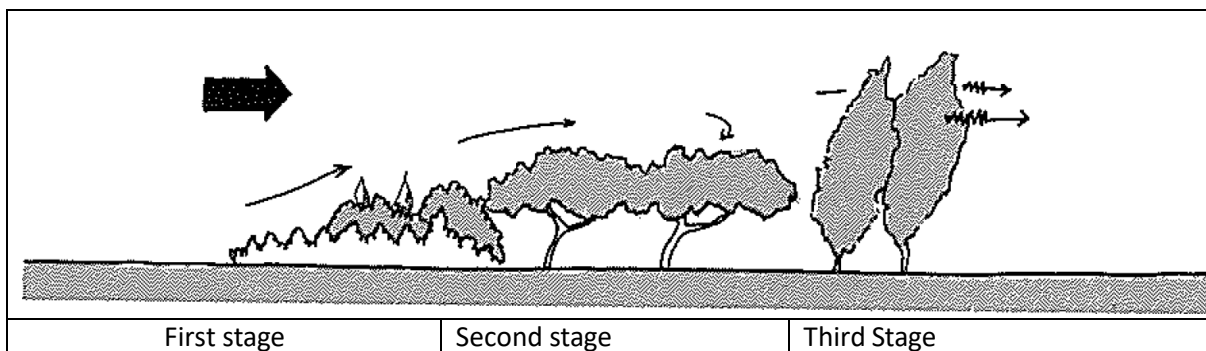


Figure 74: Stages for planted screens

A first, relatively low stage, consisting of creeping, bushy or shrubby plants, ensures “shield” protection at the level of pedestrians (cotoneaster, pittosporum, laurel, etc.).

A second stage of medium height, serving as a cover, continues the protective effect. It prevents the wind flowing back to ground level; the base can be open since it is protected by the first stage. A ball or spread vegetation can be adopted (umbrella pine, cork oak, etc.).

The third higher stage serves as a sieve and extends (depending on the height in particular) the protective effect. Erect (poplar) or conical plants are recommended.

8.9.4 The composition of the soil (natural or added) and its water supply

The chemical composition of soil directly affects the growth and development of plant species: for example, for a lime soil, the Provencal Cypress and the Judas tree are perfectly adapted; on the other hand, the bald cypress and the country elm will likely perish.

Therefore, during the implementation of vegetation, it is important to get advice from a horticulturalist.

Water availability for the plants will also need to be reported. For example, 20m³ of earth (height 1m, length 10m and width 2m) requires about 10,000 L of water per year if for a grouping of privet, cedar or cypress to grow.

The groupings of plants can also be successfully carried out in pots, in containers, on slabs and embankments.

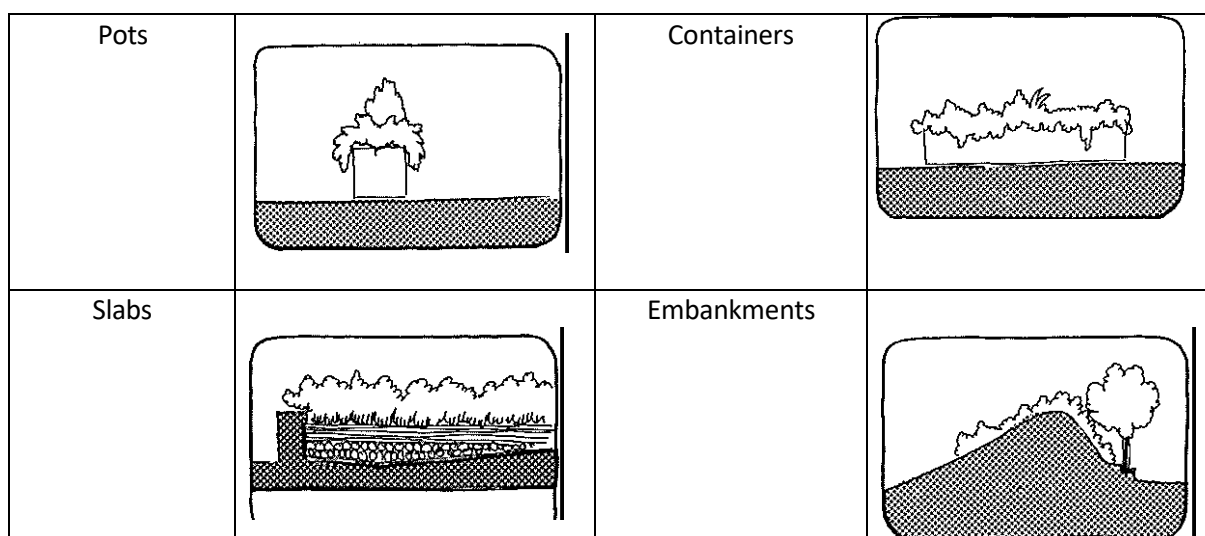


Figure 75: Showing potential vegetation placement

In all cases (natural or added soil), the volume of growing soil must be related to the plant volume. Thus, for plantings on slabs, a few tens of centimetres are enough for a low vegetation, but for groups of plants of medium height (a few metres), a minimum of 0.8 m of soil thickness must be provided.

This type of development poses the problem of overload caused especially in rainy weather where the weight of the water is added to that of the earth. In addition, it is necessary to provide for effective drainage to compensate for the disturbances linked to drainage.

The protection from planted windbreaks is increased when combined with other aerodynamic interventions (earth mounding, rockeries, artificial screens, etc.).

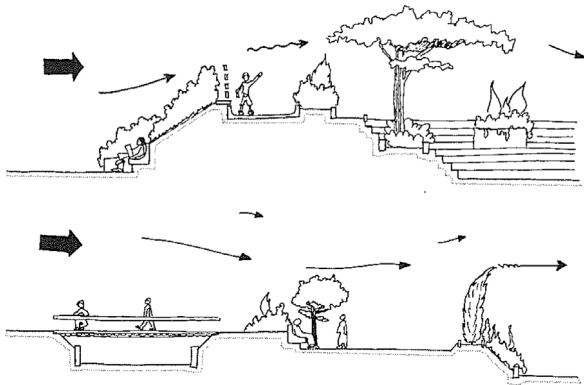


Figure 76 Examples of associations of earth mounding and planting

In addition, the richness of its other bioclimatic qualities: creation of shade (summer) and determination of light, limitation of the heating of surfaces, humidification and air purification, soil fixation and erosion control, visual privacy, etc., often make plants a preferred treatment element for outdoor spaces, if they can be supported to grow against the wind.

8.10 Constraints and implementation of artificial screens

In addition to its protective role for which it is designed, artificial windbreaks must be strong enough to resist the wind loads. For important work it is advisable to call on a design office.

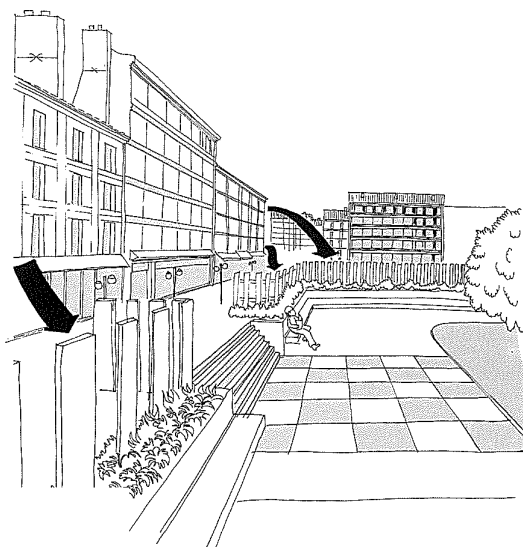


Figure 77 Example of integration of windbreaks into an urban environment

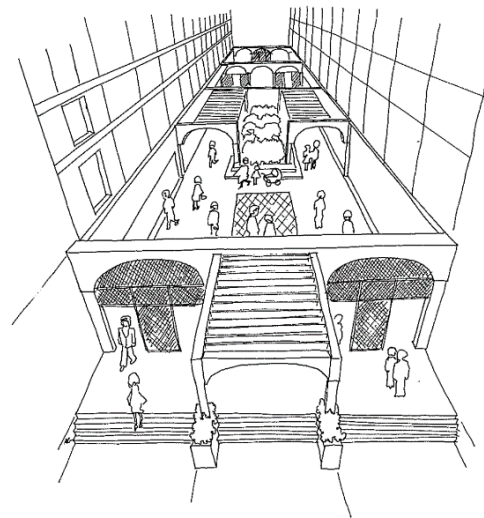


Figure 78 Constructed windbreaks in an urban environment

Like plants, an artificial wind break is part of our environment. Therefore, an aesthetic and visual interpretation will have to be found. Integration into the landscape will depend in part on the consultation between landscaper, architect and aerodynamicist.

8.10.1 Practical Advice

A windbreak, by its presence, modifies the framework of its location. One way to successfully integrate it is to make it play one or more complementary roles. Research on possibilities of

multifunction will improve its integration and even, in some cases, reduce its cost. Examples of dual functions are:

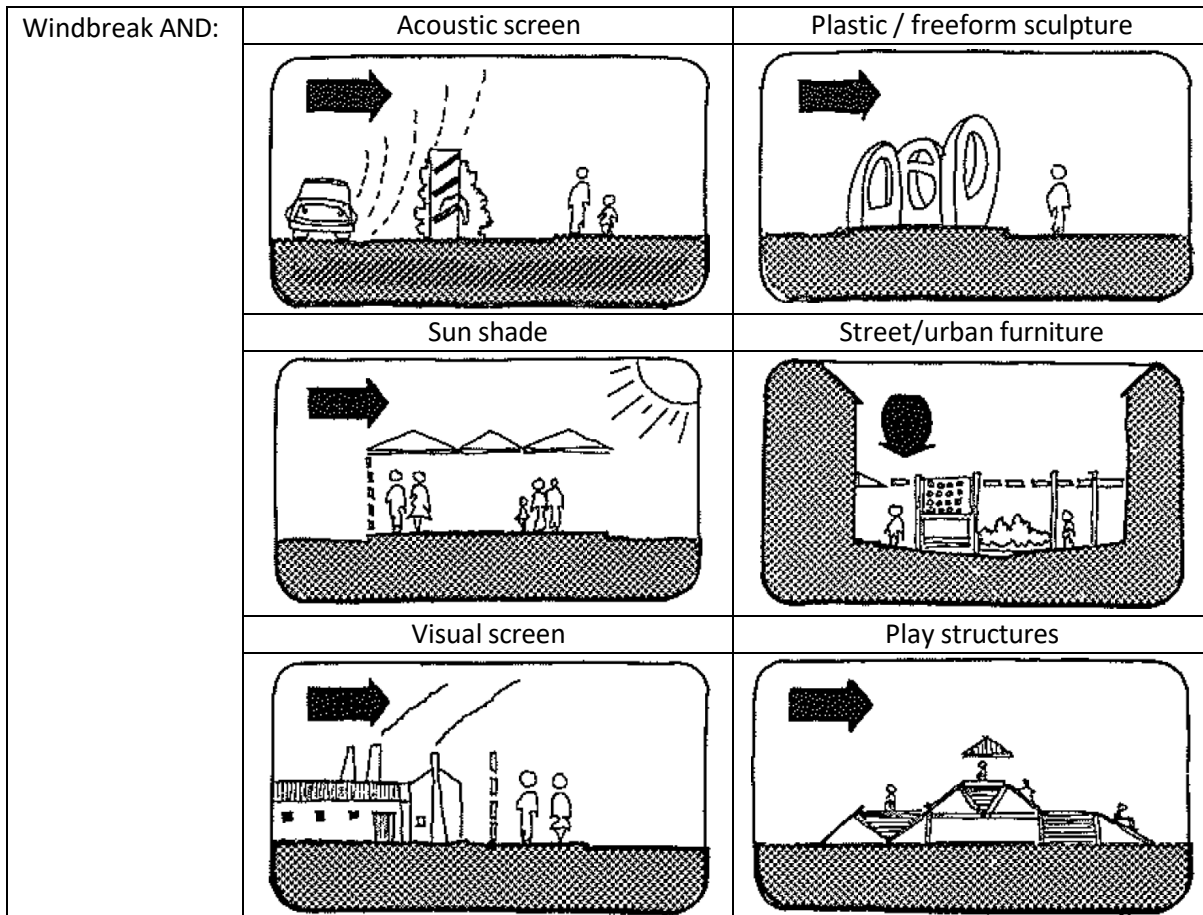


Figure 79: Wind breaks with dual function

When windbreak structures are built, other nuisances should be avoided: for example, acoustically, the use of materials such as brick, concrete or such as wood do not generate aerodynamic noise. On the other hand, light structures made of metal can introduce whistles (small elements forming a link between panels, or parasitic vibration of sheets or blades lacking rigidity).

Too much shelter should not be created to the extent that, on windless days, problems of air renewal and pollution arise. It will be necessary, for example, to preserve in the climatic development of a space, "ventilation", well positioned, which will allow a light circulation of air; again, the support of technical specialists can only be beneficial.

9.0 Conclusion

This guide is intended to provide architects, landscapers, planners and developers with information to help them understand the interaction of buildings and the wind and to control wind accelerations in outdoor areas. More generally, its aim is to enable designers to have means to design for protection against the wind.

The effectiveness of aerodynamic principles and corresponding devices is quantified according to their context of application and as far as possible general guidance has been provided in the form of many practical tips. Nevertheless, we advise designers to consult environmental aerodynamicists, especially in regard to microclimatic control in urban areas. Specific wind tunnel studies of design ideas sparked by this guide will prove a more reliable prediction suited to the specific urban context and will often be essential.

It must be remembered that the quality of outdoor spaces is a combination of all the environmental factors affected by buildings and wind shelter devices like windbreaks. Buildings can create unwelcome or useful shade impacts on outdoor spaces depending on the season or the local climate. In addition to the aerodynamic action of windbreaks, they can possess other functions such as acoustic screen, sand trap, space definition, etc. Above all windbreaks must be integrated into a specific local environment.

Consequently, far from weighing down the design of buildings or additions and alterations to existing buildings with constraints, the goal has been to identify how groups of buildings and windbreaks can support a new architectural expression, a Bioclimatic Urbanism. A goal of this guide is to contribute to freeing the architect from the environment in this way.