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Pedestrian level wind speeds in downtown Auckland

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Abstract. Predictions of the pedestrian level wind speeds for the downtown area of Auckland that have been obtained by wind tunnel and computational fluid dynamic (CFD) modelling are presented. The wind tunnel method involves the observation of erosion patterns as the wind speed is progressively increased. The computational solutions are mean flow calculations, which were obtained by using the finite volume code PHOENICS and the k-ε turbulence model. The results for a variety of wind directions are compared, and it is observed that while the patterns are similar there are noticeable differences. A possible explanation for these differences arises because the tunnel prediction technique is sensitivity to gust wind speeds while the CFD method predicts mean wind speeds. It is shown that in many cases the computational model indicates high mean wind speeds near the corner of a building while the erosion patterns are consistent with eddies being shed from the edge of the building and swept downstream.

Key words: pedestrian winds; computational modelling.

1. Introduction

In 1968 three young architects mounted a campaign of opposition to what was described as “the biggest and costliest urban renewal project in New Zealand, the NZ$36 million Auckland Harbour Board downtown development scheme”. In particular they objected to the siting of one of Auckland’s first high rise buildings at No. 1 Queen Street, see Fig. 1. They said that it “obstructed the view of the historic, elegant Ferry Building, and that its design, as well as its position, would deflect wind into Queen Elizabeth II Square and block the sun”. In order to support their case they even built their own wind tunnel in a disused factory and used smoke visualisation to produce a film which, although shown on TVNZ, failed to convince the City Council.

Thirty years later Queen Elizabeth II Square, and in particular the area around No. 1 Queen Street, has a reputation for being one of the windiest areas in central Auckland. Both recent wind tunnel and computational modelling studies support the general findings of those early tests. In this paper, which is an extension of earlier work by the authors (Richards and Mallinson 1998 & 1999), a comparison will be made between the pedestrian level wind patterns predicted by wind tunnel and computational fluid dynamic (CFD) models.

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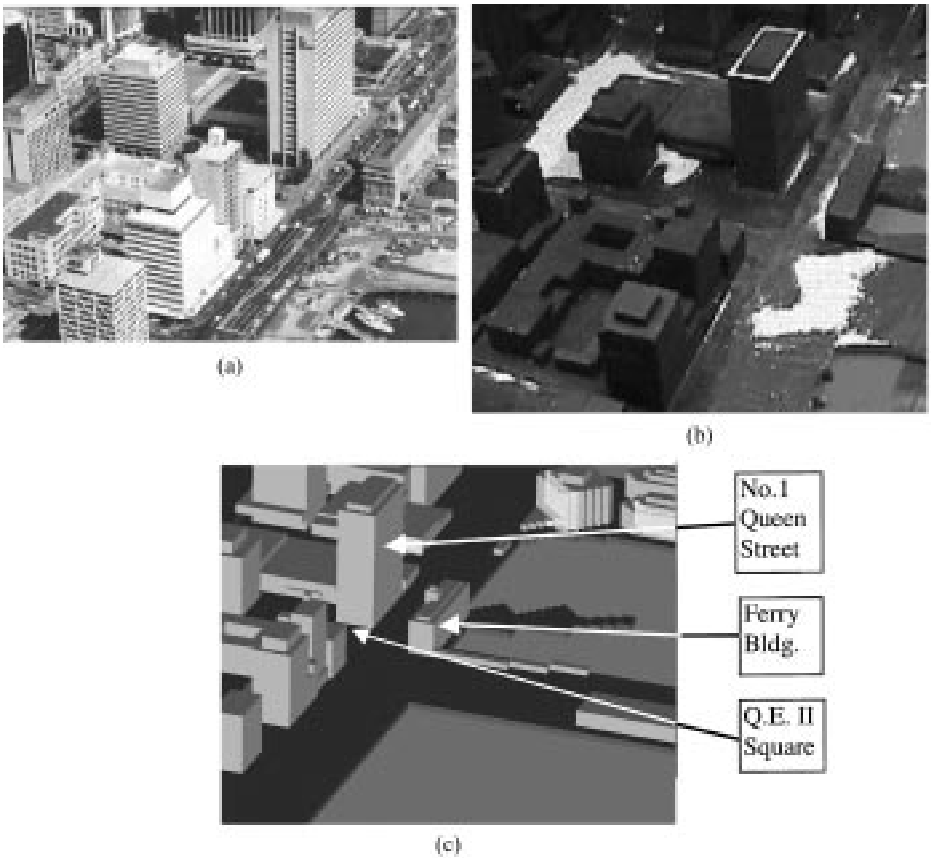

Fig. 1 (a) View of downtown Auckland from the north-east direction, (b) corresponding wind tunnel and (c) computer models

2. Pedestrian level winds in Auckland City

Pedestrian level winds in Auckland City are regulated by the requirements of the District Plan (Auckland City 1997). This document defines the acceptable wind conditions according to the purpose intended for each area. The associated categories, which are listed in Table 1, range form Category A, which includes public squares, to Category D for road carriageways. There is also a Category E but this wind condition is considered dangerous and is generally undesirable. The associated wind statistics are shown in Fig. 2. These numerical requirements are the result of advice given to Auckland City by Professor R.G.J. Flay of The University of Auckland (some aspects of which are reported in Flay 1989), who based his recommendations on the work of Penwarden and Wise (1975), Isyumov and Davenport (1976) and Melbourne (1978). As a result these recommendations are in line with recommendations originating from Britain, Canada and Australia, respectively. The general philosophy with these categories is that areas where the public are likely to spend significant periods of time should be a lot less windy than areas where they might just pass through, such as when they cross the road. What this means numerically, is that in order to be classified as Category A the hourly mean wind speed of the area must be less than 4.3 m/s for 99% of the time (P(>4.3 m/s)

Table 1 Definition of Auckland city wind categories

Category A	Areas of pedestrian use containing significant formal elements and features intended to encourage longer term recreational or relaxation use, i.e., major and minor public squares, parks and other public spaces - e.g., Aotea Square, Queen Elizabeth Square, Albert Park, St Patricks Square, Freyberg Place.
Category B	Areas of pedestrian use containing minor elements and features intended to encourage short term recreation or relaxation, i.e., minor pedestrian open spaces, pleasance areas in road reserves, streets with significant groupings of landscaped seating features e.g., Kartoum Place, Mayoral Drive pleasance areas, Queen Street.
Category C	Areas of formed footpath or open space pedestrian linkages, used primarily for pedestrian transit and devoid of significant or repeated recreational or relaxational features, such as footpaths where not covered in Categories A or B above.
Category D	Areas of road, carriage way, or vehicular routes, used primarily for vehicular transit and open storage, such as roads generally when devoid of any feature or form which would include the spaces in Categories A - C above.
Category E	Category E represents conditions which are dangerous to the elderly and infants and of considerable cumulative discomfort to others. Category E conditions are unacceptable and are not allocated to any physically defined areas of the city.

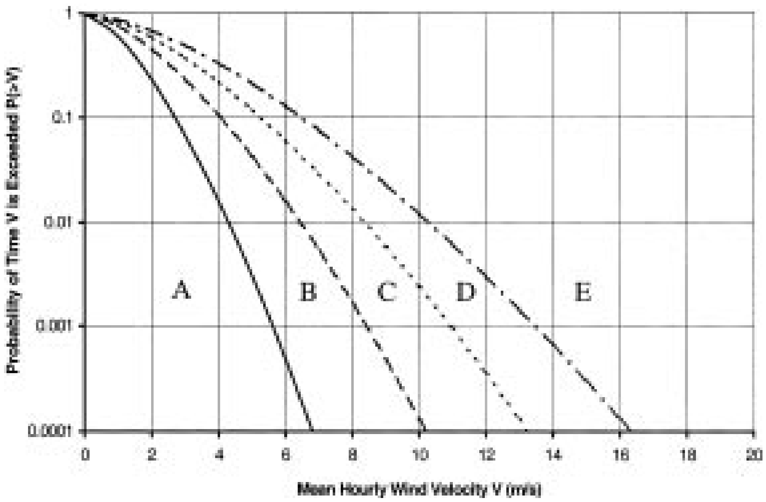

Fig. 2 Wind statistics for Auckland city wind categories

= 0.01), whereas a Category D area only requires the mean wind speed to be less than 10.3 m/s for 99% of the time. That is the wind can be more than twice as strong in a Category D area than in a Category A area.

It is interesting to note that in describing Category A, one of the areas explicitly mentioned in the District Plan is Queen Elizabeth II Square. Although it may be desirable that this square should be Category A, the reality of the current situation is that most of the square is Category C, while an area around the north-eastern end of No. 1 Queen Street is Category D.

Although the wind category statistics are specified in terms of the probability of exceedance of certain hourly mean wind speeds, wind tunnel studies of Auckland buildings have traditionally used erosion techniques which are more indicative of gust wind speeds. For many years the technique used (Flay 1991) involved the observation of the onset of erosion of cork grains as the tunnel speed was progressively increased. By knowing the gust wind speed at which erosion began and assuming a gust factor, the ratio between the local wind speed and that measured at a reference height (usually 200 m full-scale equivalent) could be established. The velocity ratios applicable to all areas of interest would be established for all significant wind directions. This data was then combined with a meteorological database, which gave probability statistics of wind strength for each direction, in order to give the overall exceedance statistics required. The main advantage of this type of technique, over point measurements, is the ability to cover a broad area and to effectively measure all points at once. However there is some uncertainty about exactly what is being measured. Livesey *et al*. (1989) have compared pedestrian level wind speeds inferred from bran erosion observations with hot-film measurements of mean wind speeds and the 1 minute and 3 second peak gust wind speeds, which correspond to gust factors of 1.5 and 3.5 respectively. They concluded that in most situations the erosion pattern indicates a gust speed equal to the mean wind speed plus about one standard deviation, that is a gust factor of 1.0. In addition they found variations in the correlation between open locations and locations near the corners of buildings.

In recent years a modernised version of the erosion technique, developed by Eaddy (Eaddy 1999, Eaddy and Flay 1999) has been used. A bed of erodible material (bran flakes) is sprinkled over the area to be tested and the wind speed increased until the bran flakes move to form an eroded pattern. During testing, a computer acquires images of these patterns and determines the erosion patterns

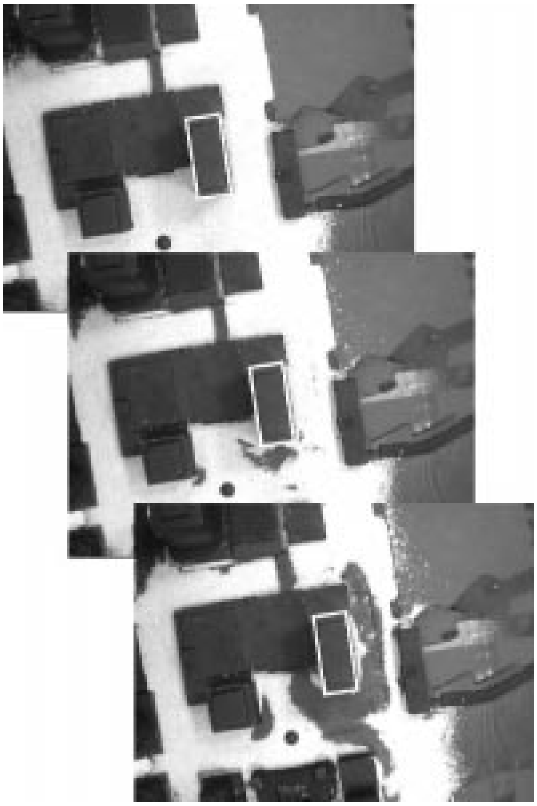

Fig. 3 Part of the sequence of wind-tunnel erosion patterns for wind direction 30°

corresponding to different wind speeds. At each stage the wind speed is held constant for about 90 seconds, equivalent to about one hour in full-scale, so that the erosion pattern is fully developed before an image is acquired. Fig. 3 shows part of the sequence of erosion patterns obtained around No. 1 Queen Street (the building with the white rectangular border) for wind direction 30^{o}.

Measurements have been made using a hot-wire anemometer to establish the wind speed, at a model scale height equivalent to 1.5 m in full scale, at which the bran flakes erode from under the wire. Having established this wind speed, the ratio between wind speed at 1.5 m and the reference point at 200 m (full-scale equivalent) may be deduced by simply noting the velocity at 200 m when erosion in a particular region occurs. It is then assumed, in keeping with general wind engineering practice, that this ratio holds for all wind speeds from the particular direction.

Once the full set of erosion images has been obtained for a particular direction, a computer image processing system is used to combine them together. The corresponding combined image is Fig. 6a. It should be noted that in these combined erosion images the contours are related to the wind speed at 200 m (full-scale equivalent) when the pedestrian level wind reaches the erosion threshold. As such the areas where erosion occurs first are the windiest areas since the ratio between the pedestrian level wind and the reference level wind is maximised.

In a full study further analysis combines the erosion patterns from each directions, with the meteorological data for that direction, in order to carry out a pixel by pixel calculation of the overall wind statistics and hence assign a wind category to each point around the building under consideration. In order to carry out this analysis all images have to be rotated and matched to each other. This is the primary function of the white border to No. 1 Queen Street, which is used to align the various images. However in the present study it is the combined erosion images for each direction that will be compared with the computational model and the overall categories will not be considered. To date computational modelling has not been used to assess new buildings in Auckland, but the potential is there for the future. The objective of the present study is to examine the similarities and differences between the current wind tunnel technique and computational modelling.

3. Wind tunnel modelling

In order to provide images suitable for comparison with computational models, a series of tests were conducted which focused on the area around Queen Elizabeth II Square and No. 1 Queen Street (See Fig. 1). This was carried out in the low speed test section of the de Bray wind tunnel located in the Aerodynamics Laboratory of the Department of Mechanical Engineering at The University of Auckland. The model scale was 1:400.

A standard layout of trip fence and roughness blocks was placed upstream of the model to produce onset flow resembling that of the natural wind. In the present case, flow over Category 3 type terrain (residential housing), as set down in the New Zealand Wind Loading Code NZS 4203 (1992) was used as the target wind structure.

Images were collected, using the techniques described in section 2, for wind directions 0^{o}, 30^{o}, 60^{o}, 240^{o} and 270^{o} as these represent the most common winds in Auckland.

4. Computational fluid dynamic modelling

Computational modelling of the flow over the Downtown shopping centre and surrounding buildings was undertaken using the finite volume code PHOENICS (version 3.2). A rectangular

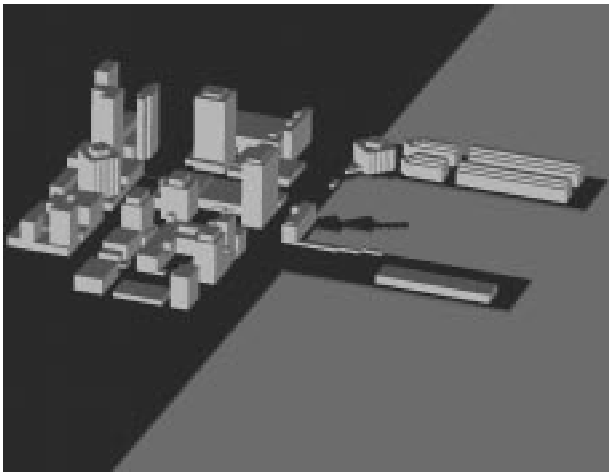

Fig. 4 The computational model of Downtown Auckland

grid, with the domain boundaries extending the equivalent of 540 m above and around the block of buildings modelled, was used. The block of buildings, see Fig. 4, extended about 400 m in each direction and was up to 80 m above Queen Elizabeth II Square, which was 4 m above mean sea level. The grid contained $150 \times 150 \times 50$ cells in the S-N, W-E and vertical directions respectively. The grid around the buildings was primarily built from 4 m cubes with some grid refinement near the ground (lowest 8 cells 1 m high and 2 m high cells up to 44 m) and around the NE corner of No. 1 Queen Street (within 40 m S-N and 32 m W-E) where the smallest cells were 2 m wide and long. Larger cells were used in the outer regions. The problem was solved in non-dimensional form, with the reference parameters being the air density, the height of No. 1 Queen Street (80 m) and the velocity in the inlet flow at that height. In this form the laminar kinematic viscosity is set equal to the inverse of the Reynolds number based on the reference parameters. In this calculation the reference inlet velocity at 80 m was taken as 10 m/s. As a result of this non-dimensioning the calculated pressure field is equal to half of the usual pressure coefficient.

A log-law boundary layer profile extending over the total depth was used with the corresponding turbulence property (k and ε) profiles specified in the manner recommended by Richards and Hoxey (1993). The standard k-ε turbulence model was used. The ground and building surfaces were treated as rough walls with the ground roughness length set to 0.2 m (suburban terrain) and the building roughness length to 0.02 m. Wall functions corresponding to a fully turbulent flow over a rough surface were used to calculate the shear forces in the near wall cells.

The computational results have been visualised by using the post-processing package SeeFD developed by Mallinson (1993).

5. Results and discussion

Fig. 5 shows a comparison of the wind tunnel and computational results for wind direction 0^{o}. In all of the plan figures (Figs. 5-7,10,11), the wind direction is directly across the page from right to left. In Fig. 5 north is to the right, but rotates with the buildings in the other figures. In both Figs. 5a and 5b the highest wind speeds are associated with the wind passing around the north-east

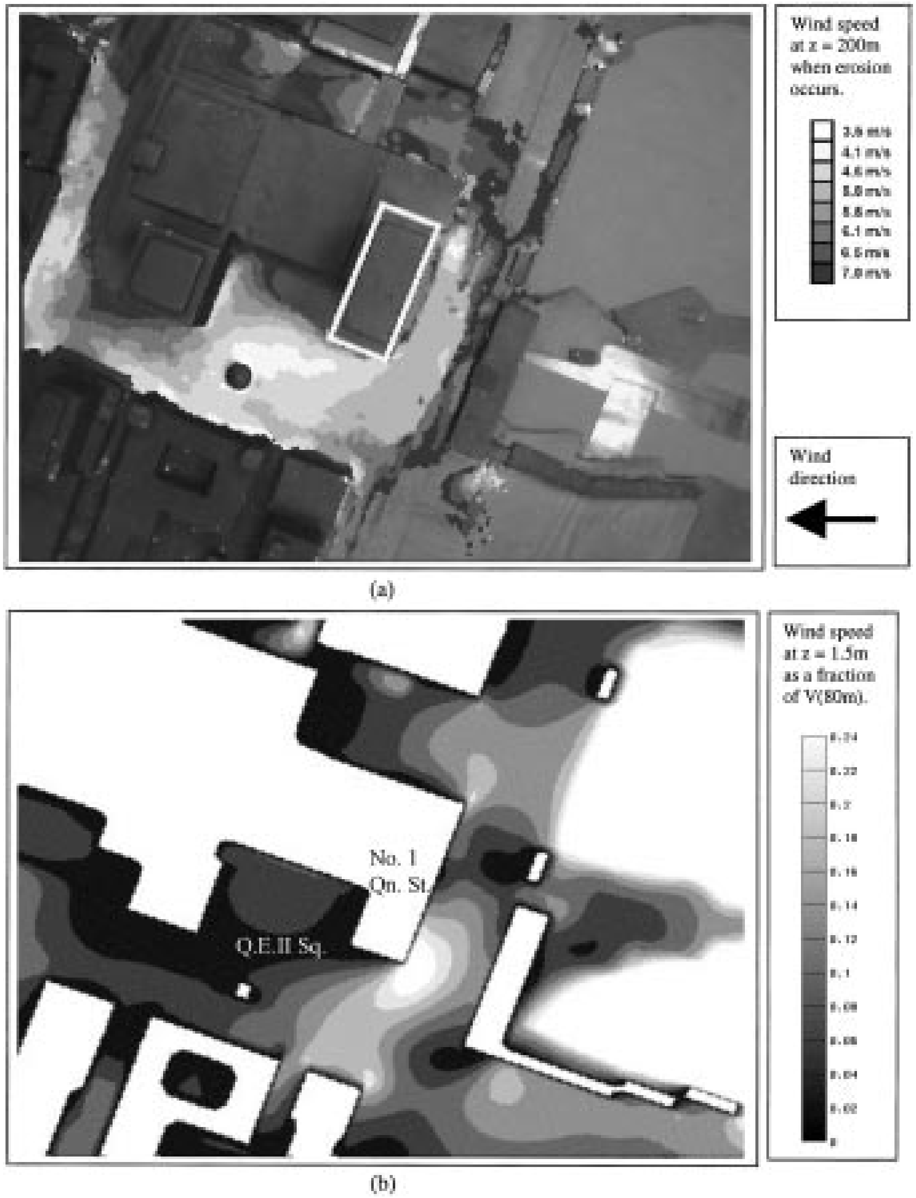

Fig. 5 Pedestrian level winds for wind direction 0° as determined from (a) erosion patterns in the wind tunnel and (b) computational fluid dynamic modelling

(lower-right) corner of No. 1 Queen Street. However there is a difference in location of the highest wind contour. With the computational solution this is located immediately around the corner, whereas the wind tunnel shows that the earliest erosion emanates from the corner and sweeps across Queen Elizabeth II Square. This suggests that the earliest erosion is being caused by turbulent eddies which are shed from the north-east corner and swept across the square.

As the wind direction changes to 30° (Fig. 6), both sets of results show a strengthening of the

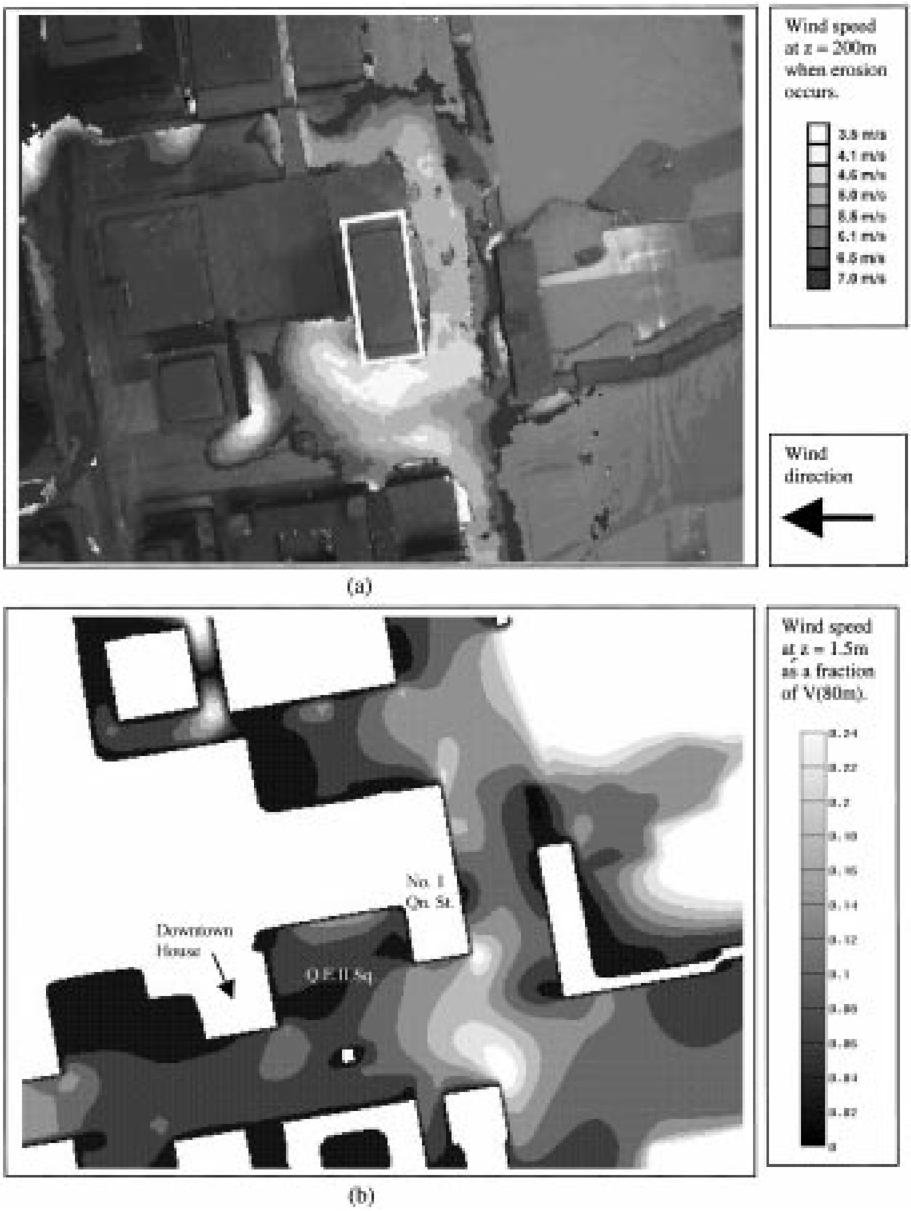

Fig. 6 Pedestrian level winds for wind direction 30° as determined from (a) erosion patterns in the wind tunnel and (b) computational fluid dynamic modelling

wind speed on the east (lower) side of the northern entrance to Queen Elizabeth II Square. In the wind tunnel, the stronger winds are still located on the west side (next to No. 1 Queen Street) of the entrance but the computational solution shows slightly stronger winds on the east side. Once again the earliest erosion locations are swept downstream relative to the highest mean wind speeds indicated in the computational solution. Both sets of results show a strengthening of wind speeds around the north-east (lower-right) corner of Downtown House and a calm patch near the centre of

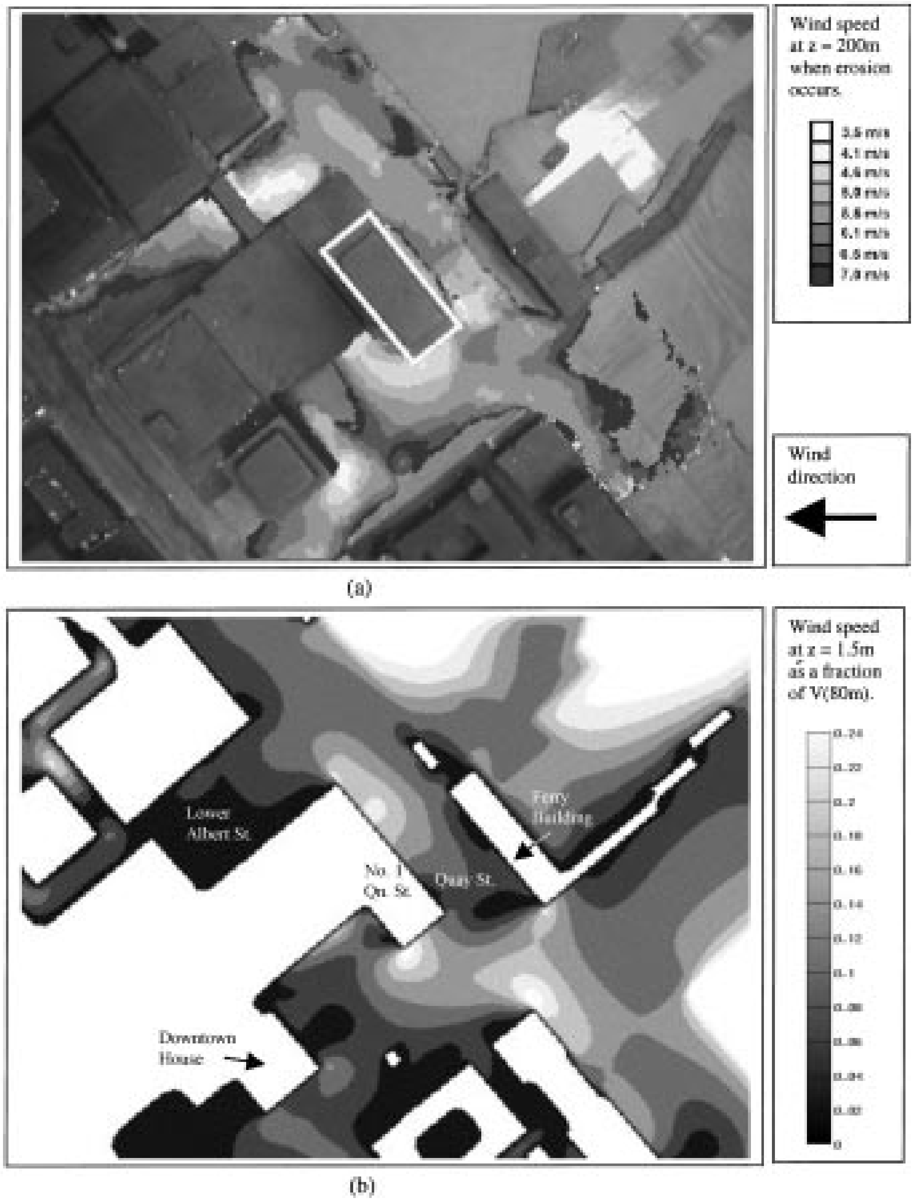

Fig. 7 Pedestrian level winds for wind direction 60º as determined from (a) erosion patterns in the wind tunnel and (b) computational fluid dynamic modelling

the north face of No. 1 Queen Street, which indicates the flow stagnating against this face.

Both sets of results show that further rotation of the wind direction, to 60º (Fig. 7), moves the windiest area adjacent No. 1 Queen Street around to the south-east corner. Other common windy areas are on the corner of Downtown House and along Quay Street. The wind tunnel also shows erosion in Lower Albert Street, which is not indicated in the computational solution. Once again it appears that the computational solution is showing high wind speeds on Quay Street adjacent to the

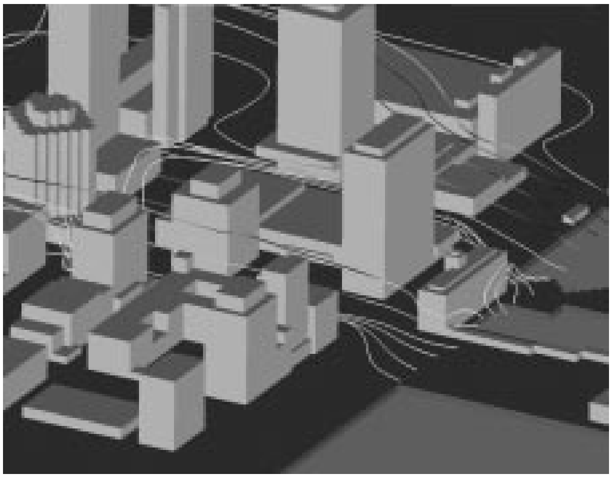

Fig. 8 Low level streamlines for wind direction 30°

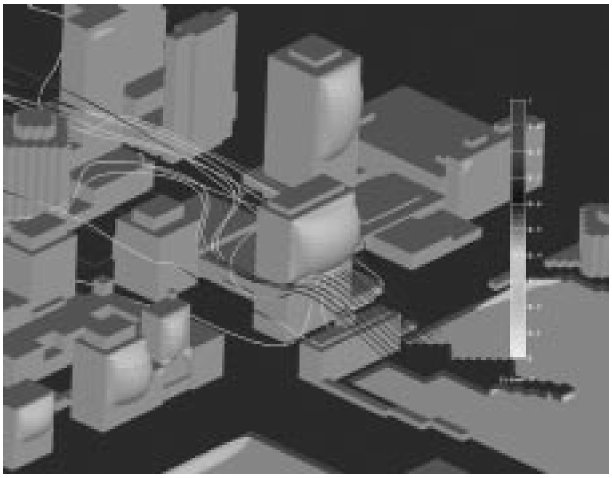

Fig. 9. $C_p = 0.7$ isosurfaces and streamlines passing over the Ferry Building

north-west corner of No. 1 Queen Street, while the erosion on Lower Albert Street is caused by eddies shed from the north-west edge.

One advantage with the computational solution is the availability of information on the total flow field rather than just ground level winds. This can be useful in interpreting results. Figs. 8 and 9 illustrate streamlines for a wind direction of 30°. In Fig. 8 it can be seen that the low-level streamlines pass around the Ferry Building and are funnelled into the entrance to Queen Elizabeth II Square. However this flow is supplemented by flow over the Ferry Building. Fig. 9 shows higher level streamlines as well as the positive pressure isosurfaces ($C_p = 0.7$) on the northern faces of the buildings. The shielding of No. 1 Queen Street by the Ferry Building means that the positive pressures are primarily confined to the upper levels and so there is a strong vertical pressure gradient. This drives the flow passing over the Ferry Building down into Quay Street and around into Queen

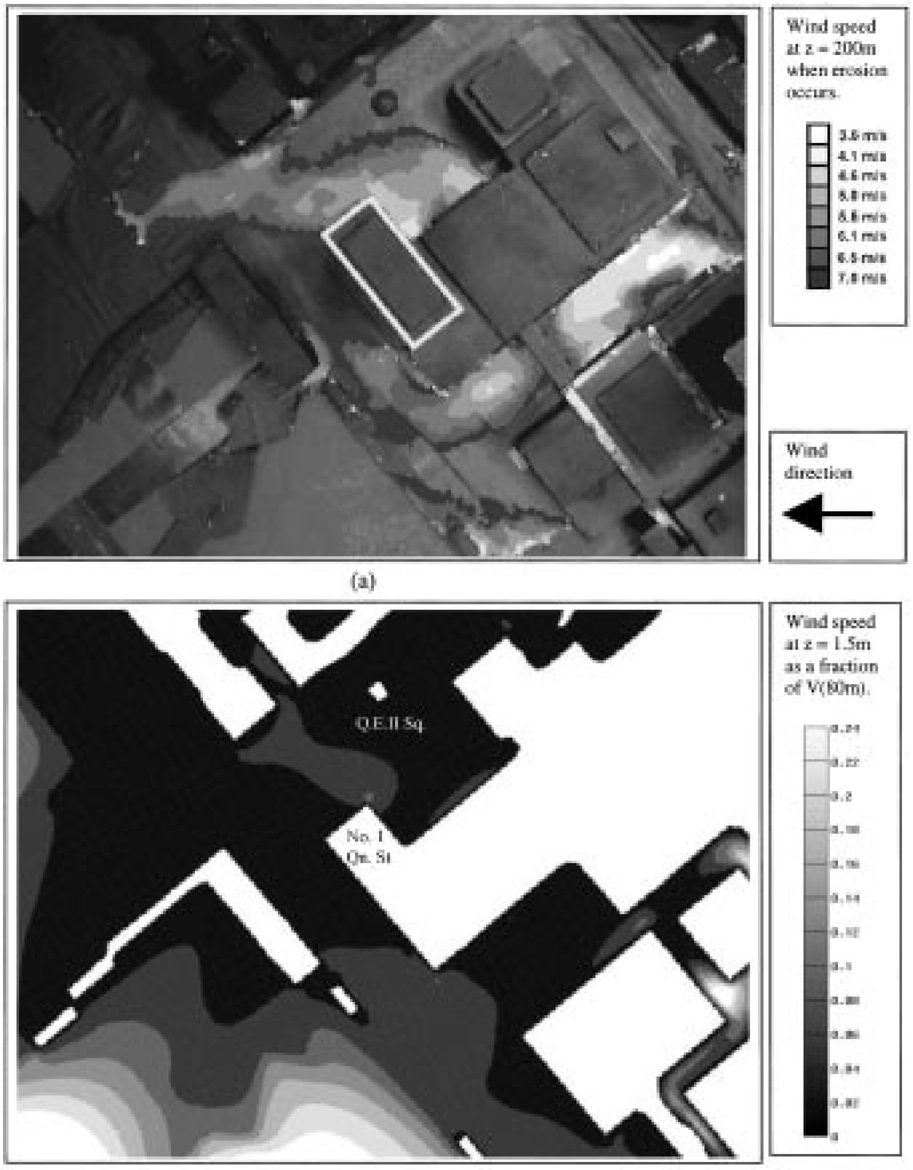

Fig. 10 Pedestrian level winds for wind direction 240° as determined from (a) erosion patterns in the wind tunnel and (b) computational fluid dynamic modelling

Elizabeth II Square.

While the entrance to Queen Elizabeth II square is very exposed to north and north-east winds, its poor reputation results from the fact that the eastern end of No. 1 Queen Street is also affected by the prevailing south-west and west winds. Figs. 10 and 11 show the results for wind directions 240° and 270°. Although the wind speeds indicated are less severe than with the north-easterly winds, both sets of results show that No. 1 Queen Street deflects winds down into the square. This is also

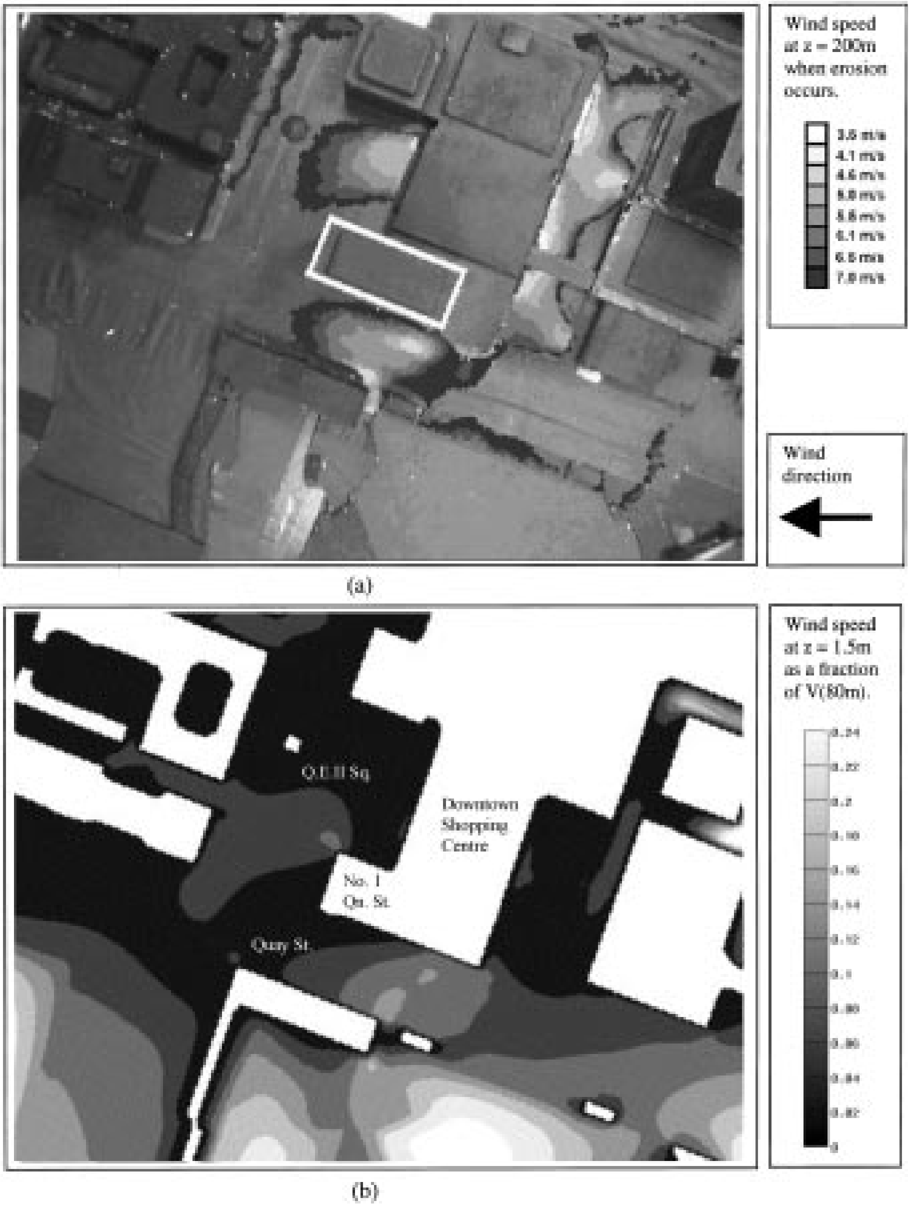

Fig. 11 Pedestrian level winds for wind direction 270º as determined from (a) erosion patterns in the wind tunnel and (b) computational fluid dynamic modelling

indicated in the streamlines of Fig. 12, where the flow passing over the downtown shopping centre is driven down into the square before exiting. It may also be noted that with the westerly winds (Fig. 11a and 11b), No. 1 Queen Street creates a windy area on Quay Street.

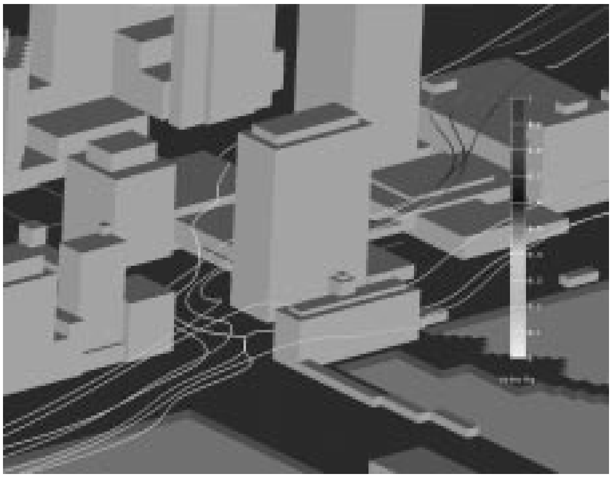

Fig. 12 Low level streamlines for wind direction 270°

6. Conclusions

Predictions of the pedestrian level wind speeds for the downtown area of Auckland have been obtained by wind tunnel and computational fluid dynamic (CFD) modelling. The wind tunnel technique used involves the observation of erosion patterns as the wind speed is progressively increased. The computational solutions are mean flow calculations, which were obtained by using the finite volume code PHOENICS and the k-ε turbulence model**.** The results for a variety of wind directions have been compared and it is observed that while the patterns are similar there are noticeable differences. A possible explanation for these differences arises because the tunnel prediction technique is sensitivity to gust wind speeds while the CFD method predicts mean wind speeds. In many cases the computational model shows high mean wind speeds near the corner of a building while the erosion pattern may be caused by eddies shed from the edge of the building and swept downstream. Further work which compares the computational model with wind speed measurements is planned.

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