Enhanced Turbulence in Terrain Category Transitions

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Abstract

A wind tunnel study of the wind profiles at the site of the Sky Tower in Auckland revealed that the transition from suburban terrain to a high rise area resulted in wind gusts greater than those expected in the suburban area. It was found that the increased surface roughness produced high mean velocity gradients with consequent high turbulence levels and high gust wind speeds. A computer model of this situation also showed similar trends. These high gust wind speeds can be of the order of 30% higher than those given by wind loading codes which predict a gradual reduction in gust wind speeds in a transition from smooth to rough terrain.

1. Introduction

The recently opened Harrah's Sky City Casino complex in Auckland incorporates a 328m high Sky Tower, which is still under construction, see Figure 1. As part of the design process Beca Carter Hollings and Ferner Ltd. (BCHF), the principal consultant and design engineers for the complex, obtained wind engineering advice from the University of Western Ontario in Canada, MEL consultants in Australia, and from the University of Auckland's Wind Engineering Unit through Auckland UniServices Ltd. One of the studies [1] conducted at Auckland University was a wind tunnel investigation of the effect of the surrounding buildings on the wind speeds at the Sky Tower site.

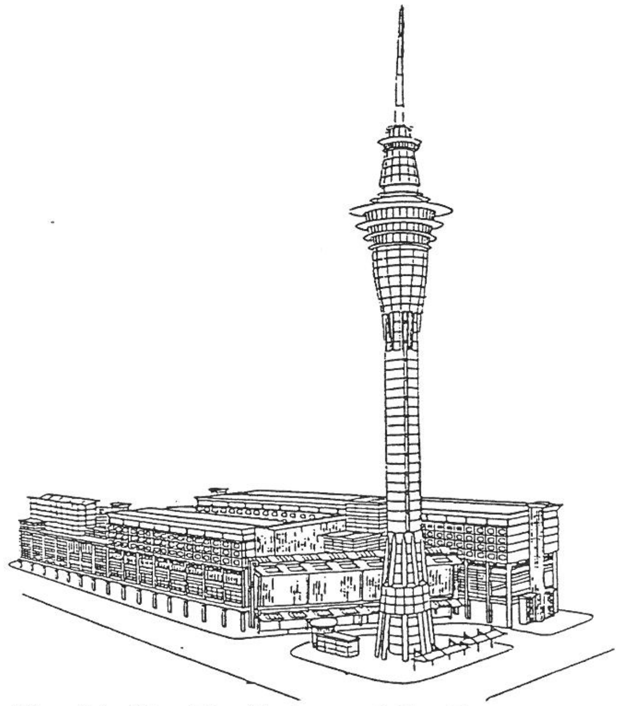


Figure 1. The Harrah's Sky City Casino and Sky Tower

2. Wind tunnel model

The Sky Tower is located on the western edge of the high rise area of Auckland's central business district. In Auckland the prevailing wind direction is SW but significant winds also occur from the NE quadrant, the latter winds approach the Sky Tower over 600m to 1km of high rise buildings and so it was primarily the effect of these buildings that was investigated. There are very few high rise buildings outside of the central business district but the surrounding area of domestic housing interspersed with patches of water is extensive. Since the area around the Sky Tower could be explicitly modelled, see Figure 2, at 1:400 scale out to a radius of 360m and in the upstream direction for a distance of 1km the terrain beyond the model could be considered to be a mixture of category 2 and 3 terrains. The New Zealand wind loading code NZS 4203:1984 [2] states that "The terrain roughness applicable at a site, for a given direction, shall be determined from the weighted average of the terrain roughnesses encountered, based on the length of each terrain within the depth of the transition zone for the particular building." For structures over 10m high the depth of the transition zone is taken as 50 times the building height. For the Sky Tower, standing 360m above sea level, the depth of the transition zone was taken as 18km. Using this approach the terrain roughness for the region beyond the central business district varied between category 2.2 and 3.0 with an average value of 2.7. Although the variation of terrain category with direction was taken into account in determining the design gust wind speeds it was decided that for simplicity a spires, grid and roughness block arrangement that modelled category 3 terrain would be used to generate the approach flow for all wind directions.

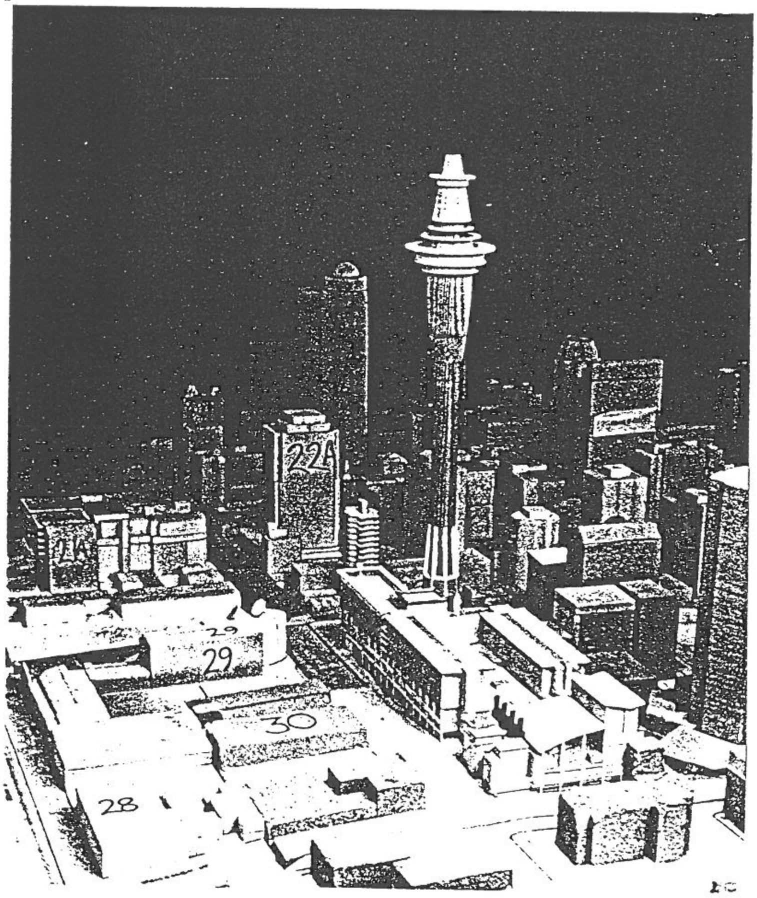


Figure 2. The Auckland model viewed from the South West with the Sky Tower in place.

3. Velocity measurements

In order to make velocity measurements at the Sky Tower site the model of the tower was removed although the model of the adjacent Sky City Casino remained in place. Vertical traverses were made along the centreline of the tower between heights of 50mm and 900mm (20m and 360m full scale equivalent). Wind velocity measurements were made using a single component 5μm diameter hot wire connected to a locally designed anemometer system. At each point the analogue output was low pass filtered at 500 Hz and sampled at 1 kHz for 25 seconds. 25 seconds in the wind tunnel corresponds to about 25 minutes in full scale during an extreme storm. A total of 13 traverses were conducted, 12 representing different wind directions in 30° intervals and a reference profile measured along the same line but with the city model removed and the terrain category 3 roughness block layout extended through the working section.

Values for the mean, root mean square (rms) and maximum velocities were recorded. The maximum velocity recorded was simply the single most extreme value obtained during each observation period, as such this maximum velocity is a crude indicator of the gust velocity used for design purposes. It is also noted that with the low pass filter set at 500 Hz the recorded maximum corresponds to an equivalent full scale averaging period of 0.12 seconds, considerably shorter than the 3 second averaging period used by Deaves and Harris [3] and incorporated into the Australian and New Zealand wind loading codes [4,2]. With this shorter averaging period it is not surprising that the average gust factor deduced from the results was 5.0 rather than the standard value of 3.7 given in AS 1170.2 - 1989 equation E.3.2.5(3) [4].

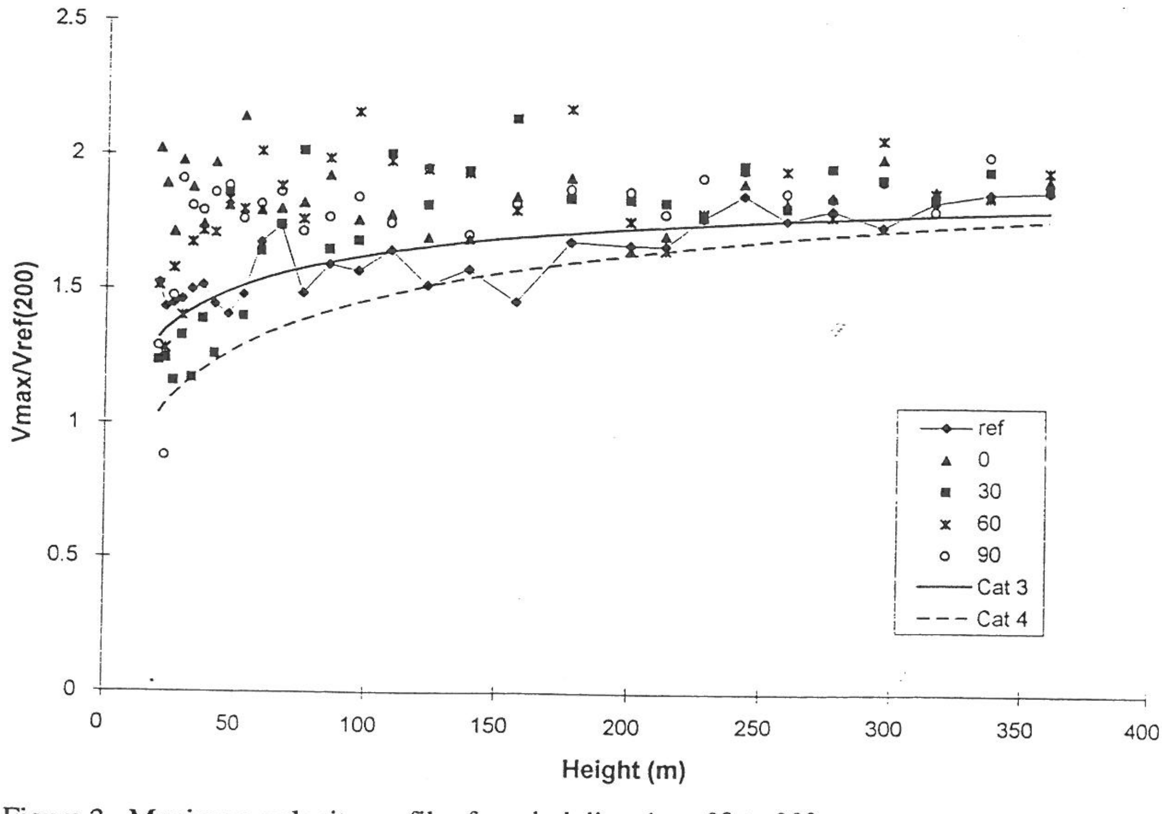


Figure 3. Maximum velocity profiles for wind directions 0° to 90°

The most interesting results obtained were those for wind directions 0° to 90°. In particular the maximum velocities, see figure 3, were, in general, greater than those obtained from the reference profile. In this figure only the data points have been shown because the inclusion of interconnecting lines results in a very confused picture. In all the graphs presented in this paper the velocities are shown as a ratio to the velocity from the reference profile at 500mm, 200m full scale, Vref(200). Also shown on this figure are the profiles that might be expected for fully developed terrain categories 3 and 4. These have been calculated using equations E3.2.5(1,3,4and 5) from AS1170.2 [4] but with a gust factor of 5.0. It may be noted that the reference profile is similar to that for terrain category 3. As mentioned in section 2 these wind directions are those for which there is a change from suburban terrain to a high rise area about 800m upstream from the site. These profiles are therefore affected by the transition from terrain category 3 to terrain category 4. As mentioned in section 3 the New Zealand code [2] treats such transitions by using a weighted average of the terrain categories within the depth of the transition zone. The Australian code [4] uses a more complex procedure which involves the calculation of the developed height of the inner layer and then uses the upstream terrain and height multiplier for heights above the developed height and a multiplier calculated from equation 3.2.6(3) at lower heights. The formula used in AS1170.2 gives a developed height of 72m from 800m of terrain category 4. With either code the resulting terrain and height mulplier lies at or between those for the two terrains involved. It appears from Figure 3 that the effect of introducing an area of category 4 terrain has increased the gust wind speeds rather than reduced them towards the values expected in fully developed category 4 terrain.

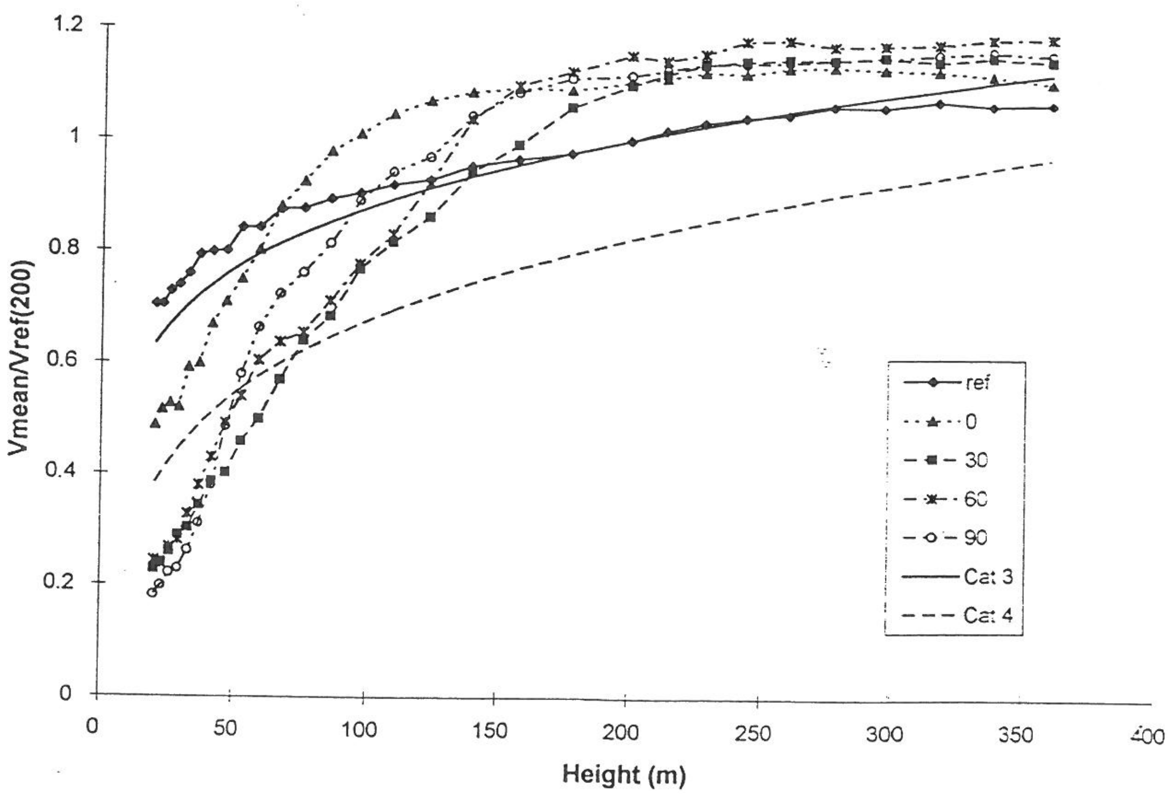


Figure 4. Mean velocity profiles for wind directions 0° to 90°

The source of these high gust velocities can be seen in figures 4 and 5. Fron figure 4 it may be noted that the high rise buildings have resulted in significantly higher velocity gradients at heights up to 200m. These increased gradients tend to leads to increased Reynolds stresses and increased generation rates of turbulence. For such turbulent flows almost all of the energy extracted from the mean flow is initially transferred to turbulence and is only dissipated by viscosity once it has been passed to the smallest eddies. The increase in turbulent kinetic energy can be seen in figure 5. The fact that at some heights the rms velocity has almost doubled indicates a quadrupling of the turbulent kinetic energy. The association of the increase in turbulence with the increased velocity gradients is clearly illustrated by the profiles for a Northerly wind (0°). For the 0° direction the upstream bulding are smaller than for 30, 60 or 90° and so the increased velocity gradient is restricted to heights below 125m and so is the range of heights for which the rms velocity is increased. For the other directions the flow is affected by much taller buildings and so the mean and rms velocities are modified up to about 200m.

From figure 4 it can be seen that the mean velocity at high heights is greater than that for the reference profile. The cause of this is uncertain. It is possible that this is caused by model blockage. Although the flexible roof of the low speed working section was adjusted to give a zero pressure gradient through the working section it is possible that some blockage effects remained. The other possibility is that this is a topographic effect. For all of these wind directions the ground level rises by 30m over a horizontal distance of 800m. In addition it is possible that the high rise buildings produce a zero plain displacement that has an additional topographic effect.

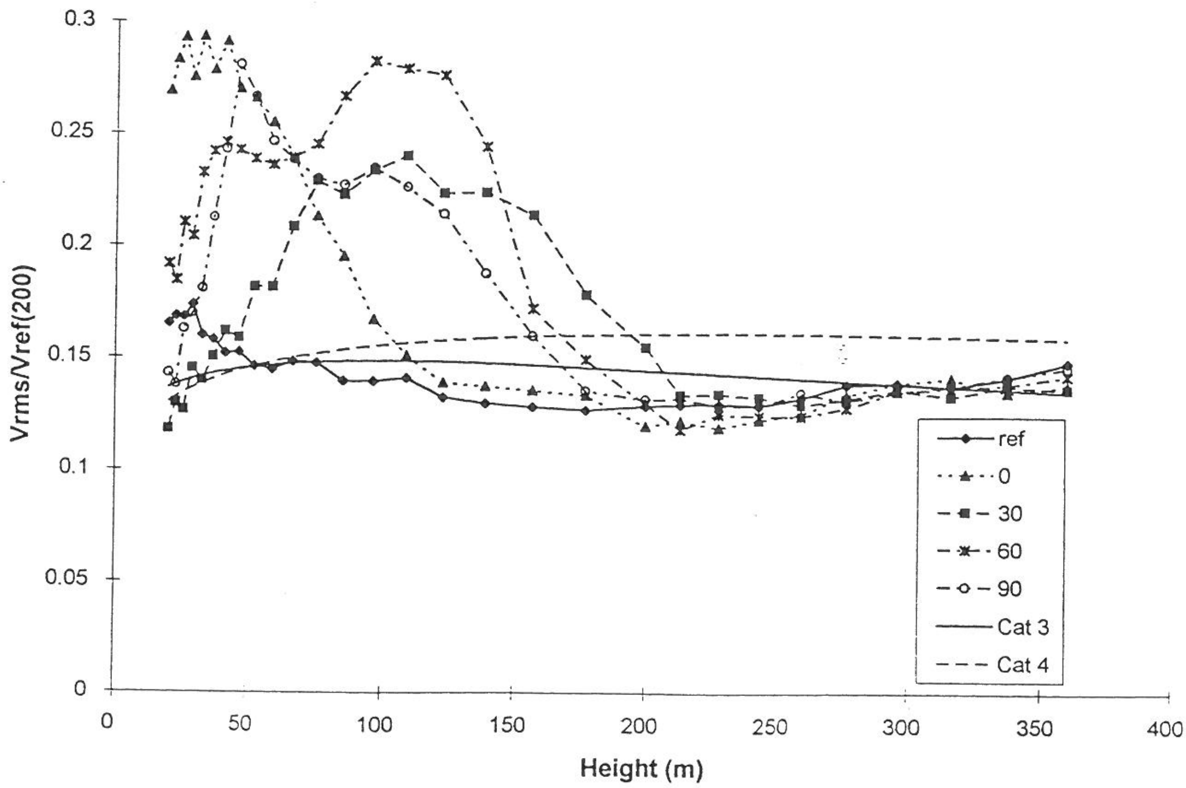


Figure 5. Root mean square velocity profiles for wind directions 0° to 90°

4. Computer simulation

As a check on the validity of the observations made in the wind tunnel a computer simulation was attempted for the wind direction 30°. The finite volume code PHOENICS was used to model a 2-dimensional section through the city. The solution domain was 1600m long and 3200m high. This high height was used in order to avoid blockage effects. A grid with 160 cells horizontally and 60 cells vertically was used. The low level cells up to a height of 200m were 10m by 10m squares. The height and length of buildings along the 30° direction were measured from the wind tunnel model and appropriate cells blocked in order to approximately model the buildings. Additional cells were blocked in order to model the rising ground level. The standard k-ε turbulence model was employed with the inlet boundary conditions based on terrain category 3 in the manner recommended by Richards and Hoxey [5]. The building blockages began 400m from the inlet. In the inlet region (0-400m) rough wall functions were used with a surface roughness length of 0.2m.

The results from the computer simulation are shown on the right hand side of figure 6 while the corresponding wind tunnel results are shown on the left hand side. The two curves shown in each figure are the reference terrain category 3 conditions and the 30° conditions at the Sky Tower site. In order to produce graphs comparable to those obtained from the wind tunnel the following approximations have been made

$$\text{Vrms (computer)} = k^{0.5} \quad (1)$$

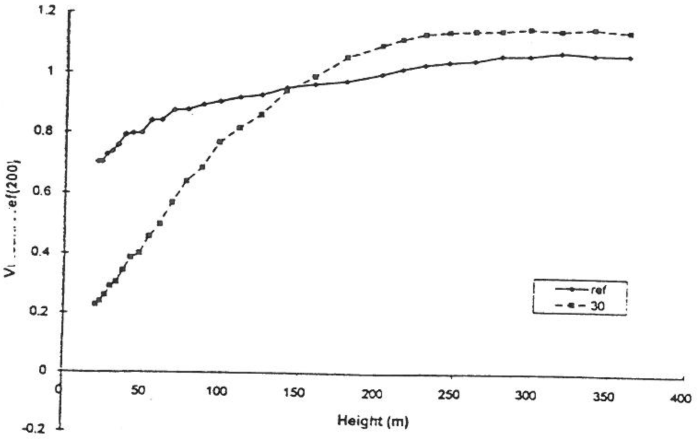
$$\text{Vmax(computer)} = \text{Vmean} + 5.0 * \text{Vrms} \quad (2)$$

where k is the turbulent kinetic energy.

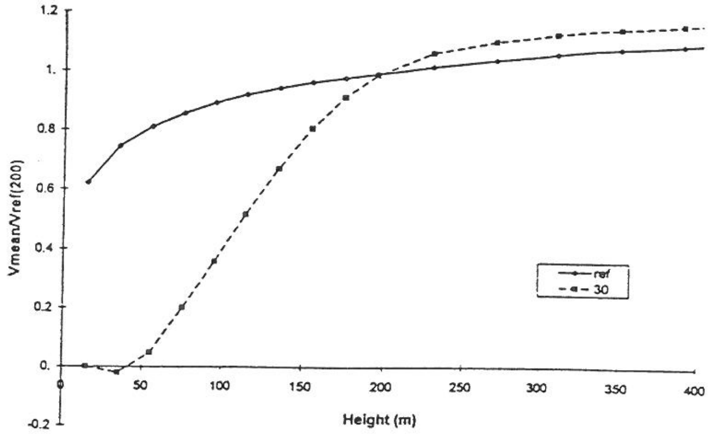
Although the results from the computer simulation are not identical to the wind tunnel results, they are qualitatively very similar. The mean velocity curves show reductions up to a height of about 200m and an increase above this. The fact that the computer model was 3200m deep tends to suggest that the mean velocity increases in the medium height range are being caused by the rising ground and the zero plane displacement created by the high rise buildings rather than artificial blockage effects that may have occurred in the wind tunnel. The rms velocity curves indicate similar increases in the turbulent kinetic energy levels in the two models. It also appears that the computer simulation suggests that the sudden transition from suburban to high rise terrain can lead to increases in the turbulence levels sufficient to give rise to increased gust wind speeds. In figure 6 a gust factor of 5.0 has been used in order to match the wind tunnel data but a very similar picture is obtained if a gust factor of 3.7 is used, in which case the predicted gust wind speed at the tower site is about 13% greater than that predicted for terrain category 3 at a height of 150m.

5. Gust wind speeds at a terrain category transition

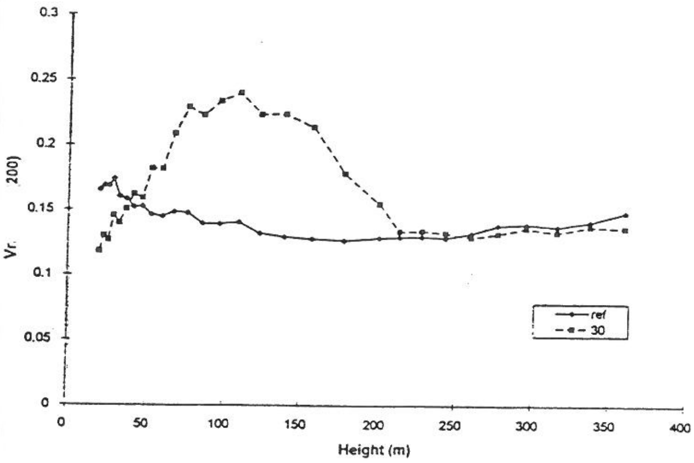
Both the wind tunnel and the computer results tend to bring into question the code provisions for treating gust wind speeds at a terrain category transition, and in particular the transition from suburban category 3 terrain to high rise category 4 terrain. In both the New Zealand and Australian codes the methods applied give a gradual progression from the higher terrain and height multiplier for category 3 to the lower multiplier for category 4 terrain. Although it is reasonable to



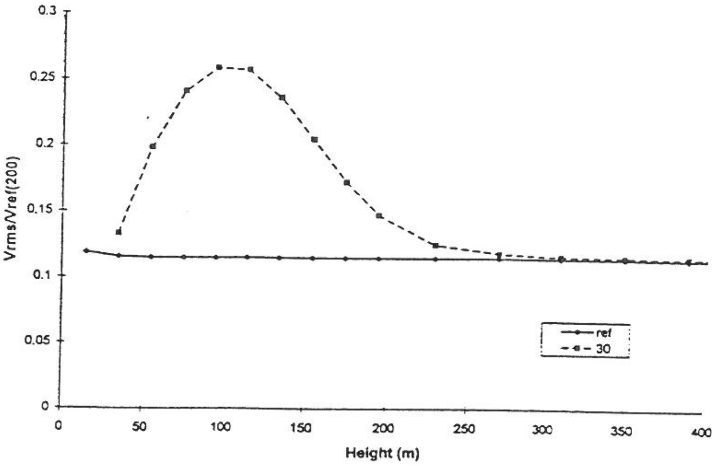
a)Mean velocity - wind tunnel



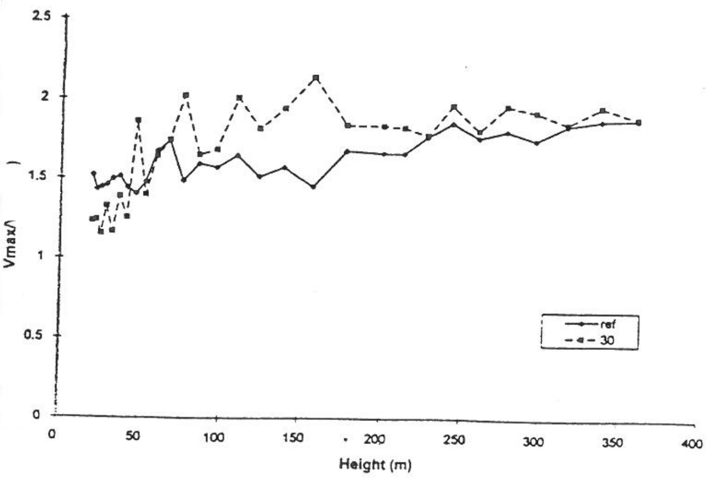
b) Mean velocity -computer



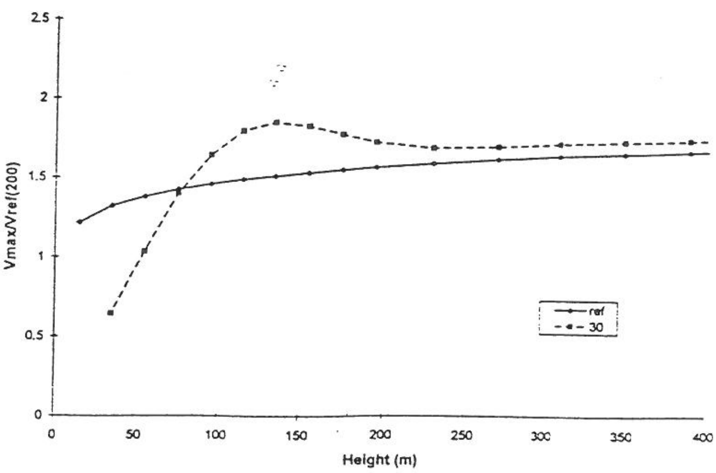
c) rms velocity - wind tunnel



d) rms velocity - computer



e) Maximum velocity - wind tunnel



f) Maximum velocity - computer

Figure 6. Comparison of wind tunnel and computer results for wind direction 30°

expect the gust wind speeds to approach the lower values after a long fetch of category 4 terrain, the results presented here show an initial increase as some of the energy contained in the mean flow over the smoother terrain in transferred to turbulence in the transition region.

It was recognised earlier that the maximum velocities measured in the wind tunnel represent a relatively short duration gust. However by using the measured mean and rms velocities and a gust factor of 3.7 such that

$$V_{gust} = V_{mean} + 3.7 * V_{rms} \qquad (3)$$

it is possible to obtain estimates of the gust wind speeds that are comparable to those given in the codes. The results are shown in figure 7. Once again it is clear that the transition is producing increased gust wind speeds, which in the worst case of the 60° direction and a height of 130 - 140m gives values that are 30% larger than even that for terrain category 3. A 30% increase in gust wind speed corresponds to an almost 70% increase in wind pressure.

As a consequence of these result Auckland UniServices [6] recommended that for cladding design on the Sky Tower at all heights between 50m and 250m (there is no cladding elements above 250m) the gust wind speed used should be that which can be expected at 250m. This represents a significant increase over the code values at the lower heights.

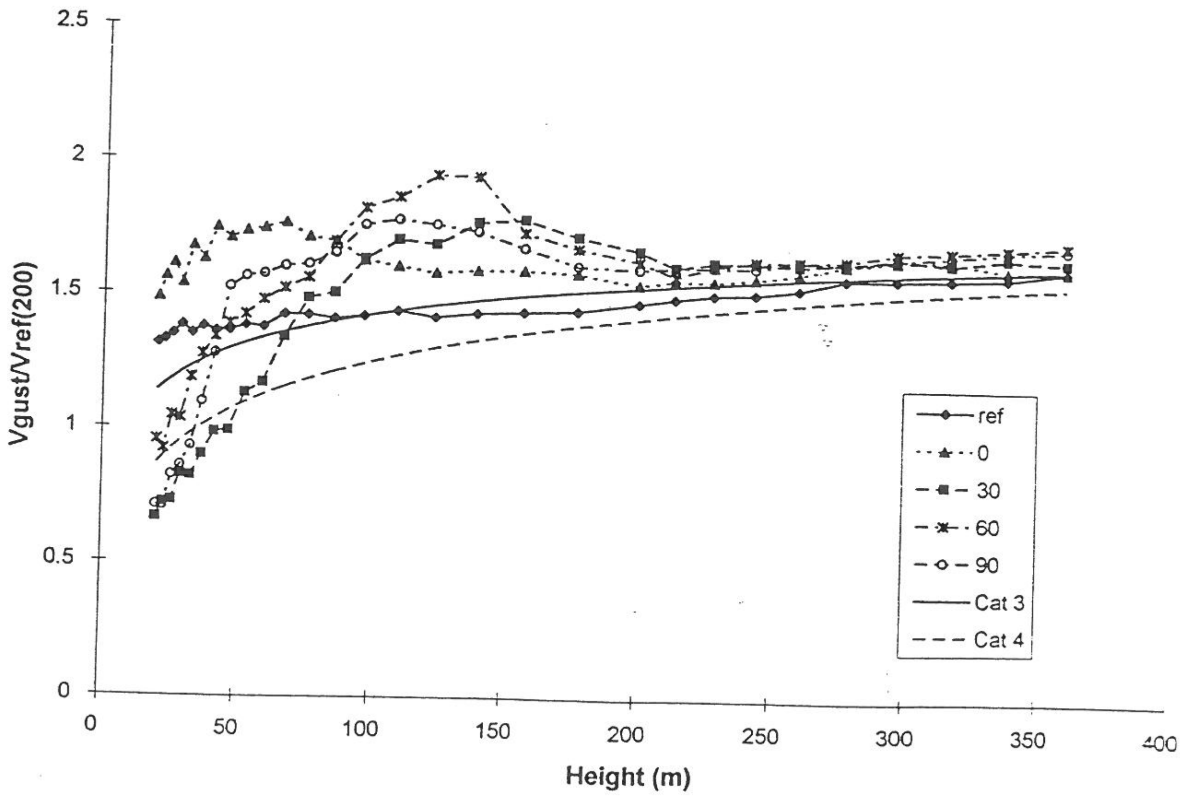


Figure 7. Gust velocity profiles for wind directions 0° to 90°

6. Conclusions

Both wind tunnel and computer modelling of a transition between suburban terrain and a high rise area have shown that this can result in high mean velocity gradients that lead to high turbulent kinetic energy levels. It has been shown that although the mean velocity is reduced the enhanced turbulence levels result in increased gust wind speeds. In the worst case these gust velocities were 30% greater than those that occurred over the smoother terrain.

Acknowledgments

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References

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