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Wind Speed Up Over Hills And Complex Terrain, And The Risk To Infrastructure

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Abstract

In an attempt to investigate the accuracy of the AS/NZS 1170.2 loadings standard, this paper presents results from a specific experiment which compares measured wind speedups over the rugged Belmont hills in the Wellington area of New Zealand with wind speedups estimated from the AS/NZS 1170.2 loadings code from two organisations, through computer (Gerris and WASP) modelling, and through wind-tunnel modelling.

It was found that computer modelling with CFD code Gerris and wind tunnel calculations agree remarkably well with observations and differentiate considerably better between areas exposed or sheltered by the local terrain compared to applying the CFD code WASP or applying the AS/NZS 1170.2 loadings code. Furthermore it was found that the AS/NZS1170.2 predictions differed significantly between the organisations. However, it should be noted that for a single location this increased accuracy does come at considerable computational cost.

Introduction

The aim of the research described in this paper is to reduce the vulnerability of New Zealand's built infrastructure to wind damage through provision of improved design wind speed procedures. Wind flow in New Zealand is strongly influenced by the hilly terrain over which it passes, with both valleys and hill crests experiencing stronger, and in some instances much stronger, wind speeds than over flat terrain. Increased wind speeds are a potential hazard for towers and pylons used to support both infrastructure and communications equipment which are often located near or on hilltops. In New Zealand, at locations far from any wind measurements, design winds are frequently estimated for such proposed structures by applying the AS/NZS 1170.2 loadings standard.

New Zealand's hilly, often mountainous, terrain is oriented approximately SSW-NNE creating a barrier 1500 to 2000 m high along both its main islands and is in the path of often strong, predominantly zonal (westerly) winds that occur at these latitudes. The wind flow is significantly modified by the hilly terrain over which it passes, with both valleys and hill crests experiencing stronger, and in some instances much stronger, wind speeds than over flat terrain. These topographic effects on wind speed are recognised in the AS/NZS Loading Standards 1170.2 [1] – a reference document for the NZ building code which prescribes the minimum loadings for buildings in NZ.

Within the Standard wind forces are prescribed as the product of the wind's dynamic pressure ($\frac{1}{2}\rho V^2$) and a shape-related pressure coefficient, C_{pe}. Topographic enhancement is allowed for with a topographic multiplier, M_t ($1<M_t<1.71$ resulting in up to 3x wind force), which depends on the hill shape and steepness, and the distance of the site from the hill crest. It also requires a Lee Multiplier, M_{lee} be applied within Lee Zones. While the physical basis for including these effects is clear, the method by which these factors are calculated is unfortunately weak and when determining Lee Zones possibly ambiguous. This fact combined with some recent severe wind events: 2004 Molesworth Windstorm [12]; 2007 Taranaki Tornadoes [11]; 2008 Greymouth windstorm [13]; the March 2010 Wellington southerly storm (in which gusts of 60 m/s and 77 m/s were recorded at Baring Head and Makara Wind Farm respectively – both with significant topographic effects involved); the 2011 Auckland EF2 tornado, also the inclusion of winds as hazard in RiskScape have caused renewed interest in wind engineering and a questioning of the guidance offered by the loadings code. Consequently the present research project was set up to provide the basis for reviewing the calculation methods in the Standard for M_t.

This paper presents some of the results from an experiment to compare measured wind speedups over the rugged Belmont hills in the Wellington area of New Zealand with wind speedups estimated from the AS/NZS 1170.2 loadings code, through computer modelling, and through wind-tunnel modelling. Further details are available in the final report on the research project [8].

Measurements of Wind Speedup

The research project was focused on measurements and modelling of topographic speed-up effects within the Belmont Regional Park near Wellington. The area, shown in figure 1, is typical of much New Zealand hill country where important infrastructure is located. The terrain is not simple - a lower ridge upstream (in a North-wester) and approximately parallel to the highest elevations adds complexity to the situation in that turbulent eddies shed from this terrain feature near mast 9, should impact the gust characteristics downstream. Furthermore the valley behind this ridge could be expected to be somewhat sheltered. Vegetation was mainly short to moderate grass with the few trees and scrub in the vicinity confined to gullies giving a design wind terrain category of 2, according to [1], although the terrain perturbations are much larger than the terrain roughness.

Nine portable masts (5 m high) with Vector A101m 3-cup wind speed sensors (accurate to 1% in the 10-55 m/s range) and Vector W200P wind vanes (direction accurate to ± 3°) were deployed. Siting of the masts was aided to some extent by prior CFD modelling with Gerris under idealised NNW flow [9,10], but the main consideration was reasonable access to the masts from roads/tracks in the park.

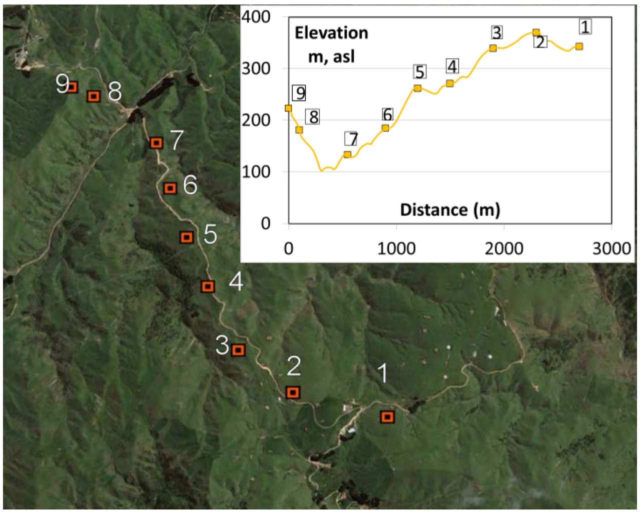

Figure 1 A Quickbird image (courtesy of KiwiImage) looking down on the typical New Zealand hill-country of Belmont Regional Park near Wellington, with locations and profile of heights for the portable masts.

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

Full-scale Speedup Observations

Several sets of full-scale measurements of wind speed were made over the first 6 months of 2011. While a design wind event was not anticipated in such a short period, several strong northerly/north-north-westerly events did occur although they were less frequent than normal due to the La Niña that dominated during this time. The paper focuses on the 18-hour observation period from 12noon on February 6 to 6am on February 7, 2011 when the wind direction was approximately 345°. Figure 2 shows the site looking upwind for this direction. Three-second wind observations were collected at all 9 masts during this period. Means, maxima, standard deviations, turbulence intensity plus directions of average and maximum winds for this period are displayed in figure 3.

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

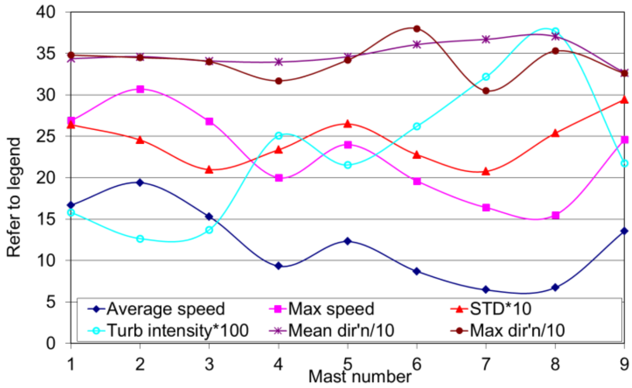

Figure 3 Belmont wind statistics for 6 - 7 February 2011 (Average speed (m/s), Max speed (m/s), STD*10 (m/s), Turbulence intensity*100 (%), Average direction/10 (degrees), and Max direction/10 (degrees)).

Figure 3 shows that: the wind direction is nearly constant across the grid from about 345° except at the sheltered masts 6, 7 and 8; the average speed and the maximum gust vary very similarly across the masts; the standard deviation (STD) of the wind speed is fairly constant at about 2.5 m/s across all the masts; the maximum gust at each mast is given within a few % by the mean speed plus 3.7*STD.

In order to determine hill-shape multipliers based on these observations, an estimate of the wind at a 5 m elevation at a neighbouring site at a location not affected by the Belmont Hills was required. Wellington Airport has one of the most reliable wind records in the region and earlier research [3], indicates that the winds there are in general larger by a factor of 1.1 compared to neighbouring locations unaffected by topography. Hourly means and maximum wind gusts are available at 7 m at Wellington Airport so in order to establish the speedups as determined by the observations, these values were adjusted to a height of 5 m and by the 1.1 channelling factor mentioned above for each of the 18 one-hour periods for which the Belmont observations were available.

AS/NZS 1170.2 Loadings Standard Speedup Estimates

The Wind Loading Standard [1] has provision for determining the effect of hills on the wind speed. It is a simplified approach, based on various published data from a number of wind tunnel tests, as well as full scale measurements. When one attempts to apply this procedure to the Belmont Hill that was used for the full-scale experiments, it is immediately apparent that the procedure is very difficult to apply. The procedure is based on 2D hills, whereas the Belmont Hill is very much 3D. Furthermore, the full-scale measurements are along a ridge as shown in figures 1 and 2.

The approach in the Standard requires the user to look upwind over an arc of +/- 22.5° with respect to the direction under consideration, and to determine the worst case for the topographic multiplier. This means that one needs multiple contours through each point of interest in order to determine the Hill-shape multiplier, M_h. Such a process would be regarded as very time consuming in a building design situation, as it would mean that many hill profile contours would need to be obtained and analysed.

Calculations for the gust hill-shape multipliers were carried out for each of the mast locations using the AS/NZS Loading Standards 1170.2 [1] for the 345° wind direction by NIWA. This involved using software that had been developed by NIWA to implement the speedup method of [1], but on close inspection, it appeared that the approach did not follow the method set out in [1] exactly, and for example, in the case of a large complicated hill such as being studied in the present research project, the method did not determine a flat "upwind" location as the beginning of the hill, but considered bumps or hills on the larger scale hilly terrain. The estimates from NIWA are given in figure 4. Because they were very sheltered, AS/NZS 1170 estimates were not performed for mast locations 6 and 7 by NIWA.

Independent estimates of the speedup were also made by the University of Auckland (UoA) using the procedures outlined in AS/NZS1170.2 [1] and its commentary, except that only the 345° direction was analysed, not the worst contour in upwind 22.5° arcs, as specified in [1]. Difficulties in dealing with the valley shown at top-left of figure 1, and near the top of figure 2 resulted in the UoA carrying out two sets of predictions of wind speedup. One set assumed that the "hill" started at the sea, and the other set assumed that the large valley between masts 6 and 9 could be assumed to be flat, thus resulting in the "start" of the hill at this location for masts further downwind. For the latter calculations, the speedup at masts 6, 7 and 8 are really undefined, since they are in the valley, and thus one would expect these masts to be relatively sheltered from wind at 345°. Mast 9 was assumed to be on the crest of an upstream hill starting at the sea. The speedup predictions for the gust speed are shown in figure 4. It is clearly evident in figure 4 that the estimates using AS/NZS1170.2 from NIWA and UoA are very different. This means that the Standard is very open to error in its use in such complex terrain, which is very common in New Zealand. This is a very interesting result, which is some cause for concern, and may mean that this section in the Standard on the Hill-shape multiplier should be subjected to a rewrite in the future to reduce possible ambiguity and possible error in order to reduce the potential hazard of wind and the risk to important infrastructure [4,6,7].

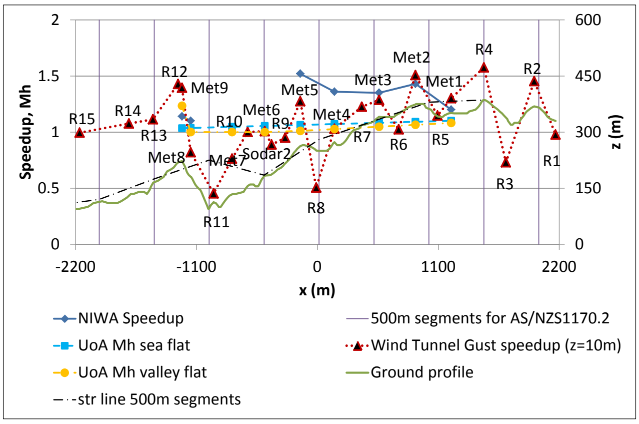

Figure 4 Ground contour along the measurement line, 500 m segments upwind from the crest, and gust speedup from the wind tunnel, NIWA using AS/NZS1170.2, and UoA using AS/NZS1170.2. Two sets of UoA results are shown. One set assumes that the "hill" starts are sea level. The other set assumes that the "valley" is flat, and that the hill for masts Met 1 to Met 5 starts at an elevation of 225 m.

CFD Estimates of Speedup

The potential flow solver WASP, developed by the Wind Energy Division at the Technical University of Denmark was used to predict speedup. It is a widely used wind energy and wind engineering tool. WASP is described in [14] and is similar to models based on [15]. For the WASP calculations undertaken herein, terrain data were from a 20 m contour DEM and terrain with characteristics of Terrain Category 2 [1] with a roughness length z_0 = 0.02 m. Calculations were done at 40 m intervals on a grid orientated at 345° to N, covering the Belmont study site for an altitude of 5 m. Hill-shape multipliers for the mast locations ranged between 0.74 at Mast 7 and 1.72 at Masts 2 and 9, although some other locations had higher values.

CFD modelling was also done using the code Gerris, which uses a time varying, adaptive grid to solve the Navier Stokes equations, as described in [9]. The topography was based on high resolution terrain contours every 5 m in the vertical direction and the Gerris model resolution is 10 m in the vertical and 40 m in the horizontal direction at the highest resolution. The model was run for 20 minutes of simulated time to allow the flow to settle down and then statistics (means and standard deviations) were generated over the next 20 minutes at heights of 5 m at each mast location. The inflow condition was a wind from 345° with a logarithmic vertical profile based on a roughness length of 20 mm and a speed of 20 m/s at 500 m – Terrain Category 2 [1]. A free slip lower boundary condition was used and it was assumed that the dominant turbulence production in the lower layers would be created by flow separation off the fairly rough upstream terrain. No parameterisation of sub-grid scale turbulence was added to the model. Comparison between the observations and the results of the model simulations for this flow can be seen in figure 5. Apart from at the easternmost Mast 1, there is remarkable agreement between observed and model simulated average speeds at the masts with a correlation of 0.96 and an explained variance of 0.89. The STD of the wind speed is very close to 3.5 m/s across the mast array. This is a little higher than the observed STD of about 2.5 m/s across the masts and is probably explained by the lack of a sub-grid scale turbulence dissipation scheme. At this resolution, it is clear that the Gerris CFD model is representing the mean modification of the incoming flow by the orography very accurately.

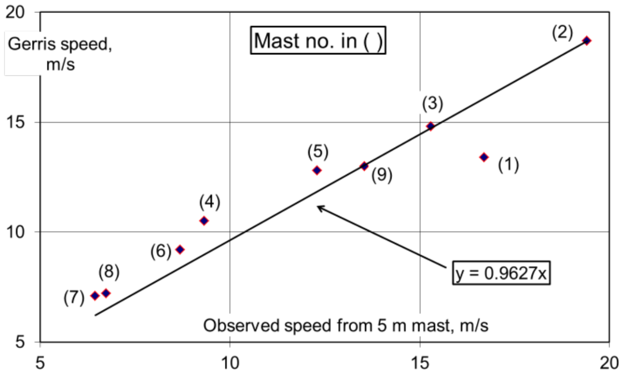

Figure 5. Observed versus Gerris modelled mean wind speeds in m/s at the selected sites in the Belmont Hills.

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

Wind Tunnel Study

The wind tunnel tests were undertaken by Opus and full details are available in [2]. A scale of 1:2000 was selected for the wind tunnel model. The Opus wind tunnel turntable is 2.6 m in diameter and allowed a full-scale diameter of width of 5.2 km. It was necessary to include at least this much area of the Belmont Regional Park study area, in order to be able to include an adequate area of model upwind of the measurement sites.

The wind speeds at an equivalent height of 5 m (2.5 mm) were measured using a single-wire hot film anemometer probe with the wire horizontal. The wind speeds were recorded at 1000 Hz, typically for 1 minute at each location. As well as other locations, the wind tunnel measurement locations included the following:

the locations of the nine NIWA 5 m high cup anemometers; the two NIWA SODAR locations; a permanent tall mast on the site; additional locations between the NIWA cup anemometers; additional locations to the north and to the south of the NIWA cup anemometers, in an approximate line approximately 4.4 km long along bearing 340°.

Results from the wind tunnel study for the gust speedup at the locations of the 9 full-scale masts, as well as some additional locations are given in figure 4 where they are compared with the predictions from the other methods.

Discussion and Conclusions

In order to attempt to answer the question – "How good is the AS/NZS 1170 loadings code at estimating wind speedup over hills in rugged terrain?"– observed speedups in the Belmont Hills region of Wellington have been compared with speedup estimates based on: the AS/NZS 1170.2 Standard, the CFD model WASP, the CFD model Gerris and the OPUS wind tunnel.

It was found that in this complex and rugged Belmont Hill region terrain, where shedding of eddies by upstream hills is likely to have an important influence on wind speeds, and the presence of valleys and ridges along the wind direction further complicates the picture, CFD modelling with Gerris or scale modelling with a wind tunnel differentiates very well between the regions where the flow is sped up and slowed down. Results are within 15% and frequently within 5%. A simple potential flow solution with some adjustment for roughness changes using the WASP program gives less accurate results – tending to overestimate both the speedups and sheltering. Assessments of winds based on the AS/NZS 1170.2 Loadings Code struggles to differentiate as well between sheltered and exposed sites– tending to produce variable estimates of design winds depending on the assumptions made by the person carrying out the estimate. Unfortunately, modelling a given site with Gerris or a Wind Tunnel is more expensive (roughly twice the cost) than applying WASP and considerably more expensive (roughly ten times the cost) than applying the Loadings Standard (costing a few hundred dollars for a single site calculation).

In terms of practical advice for someone wanting to estimate a design wind speed in a remote location with rugged topography, the following comments are made. The loadings code generates a result for a single point whereas the wind tunnel and CFD methods generate values over a large 10 km square at 100 m resolution – potentially for many points. For an isolated single location it may be cheaper to apply the loadings code, but because of the potential inaccuracies in the method, it may be necessary to be conservative (apply an over-estimate of the wind speedup). Depending on the size of the proposed structure this may lead to a considerably larger building cost – potentially far outweighing the extra cost in estimating the wind speed more accurately. If estimates at many (more than 10) locations are required in a given 10 km square then it will almost certainly be more cost effective to use a CFD or wind tunnel based method.

It should be noted that these results are based on one eighteen hour period of strong winds from a specific direction at a single location. It is intended that further research will be carried out at this site to confirm more generally the relative merits of the various methods for other locations and wind directions.

Acknowledgments

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