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Study of wind speeds over hilly terrain using full-scale observations, wind tunnel simulation and CFD

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Abstract

Wind speed hill shape multipliers have been analysed for a hilly study area near Wellington, New Zealand, using a range of measurement and calculation procedures. The results from full-scale observations, wind tunnel, and Gerris CFD simulations agree well with each other. Wind speed hill shape multipliers calculated using the Loading Standard AS/NZS1170.2 differed from the other procedures, and also differed markedly between the organisations using AS/NZS1170.2 .

Introduction

The New Zealand Wind Engineering Research Consortium includes NIWA, Opus International Consultants, the University of Auckland and GNS. The consortium has investigated wind speed hill shape multipliers measured in the field, and compared these with computational fluid dynamic (CFD) computer modelling and wind tunnel testing, with the view to comparing these results to the provisions of the Loading Standard AS/NZS1170.2. The aim of the research is to reduce the vulnerability of the built infrastructure to wind damage through provision of improved design wind speed procedures.

AS/NZS1170.2 provides a range of modification factors which, when applied to the various basic regional wind speeds, account for changes in upreach ground roughness and associated vertical wind profile, topographic enhancement (channelling, hill shape and orographic) and shielding from surrounding obstacles. The largest modifier is the hill-shape modifier, Mh with a range 1~1.73. Consequently, the hill shape modifier can increase the wind pressure three fold over adjacent sites on flat terrain. This, combined with New Zealand’s renowned hilly and mountainous terrain, puts the hill shape multiplier as being of primary importance when deriving wind actions.

Aspects of the research has been reported Turner et al (2011), Flay et al (2011), Carpenter et al (2011), Revell et al (2011), and Moore et al (2012).

This paper summarises the whole research, and pays particular attention to the results of the wind tunnel study.

Study area selection

The hills of Belmont Regional Park were selected as the study area. The features of this area making it suitable for the study included:

- Proximity to the Wellington-based research organisations.
- Ease of access by vehicle track to the site.
- Frequent strong winds.
- Grassy landscape, with few trees or buildings.
- Highly complex topography, including multiple hills (up to about 400 m high), ridges and valleys.

For the prevailing north to north-west wind directions, the study area rises fairly steadily from sea level. The study area is about 4 km from the Porirua Harbour coastline, with the suburb of Cannons Creek lying between the coast and the test area.

Site wind speed measurements

The site wind speed measurements have been undertaken by NIWA. Nine cup anemometers were located on 5 m high portable masts, in an approximately 2.5 km long line. The instruments were 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°). Measured gust speeds were averaged over 3 seconds. The anemometers are identified as locations Met1 to Met9. For northerly and north-westerly winds, anemometer Met9 is at the upwind end of the line. Met1 to Met7 are on a ridge along an approximate NNW bearing, with the highest elevation being at Met2. Met8 and Met9 are on an upwind ridge lying approximately normal to the main ridgeline. Additional wind speed data was obtained using two sodar instruments. Analysis of the sodar data has not been included in this paper.

Several strong northerly and north-north-westerly wind events were recorded over the first 6 months of 2011. The wind speed data in this paper was obtained during an 18 hour period from noon on February 6 to 6 am on February 7, 2011. The measured wind direction was 345 degrees, and was fairly constant across all of the more exposed anemometer locations.

The measured wind speeds at the site were compared to the wind speeds measured at the permanent anemometer station at Wellington Airport, in order to calculate the hill shape multipliers for the study area.

Figure 1 shows a view of the wind tunnel model of the study area, with the locations of Met1 to Met9 shown.

Figure 2 shows a plan view of the topography showing all the wind tunnel measurement locations, including Met1 to Met9.

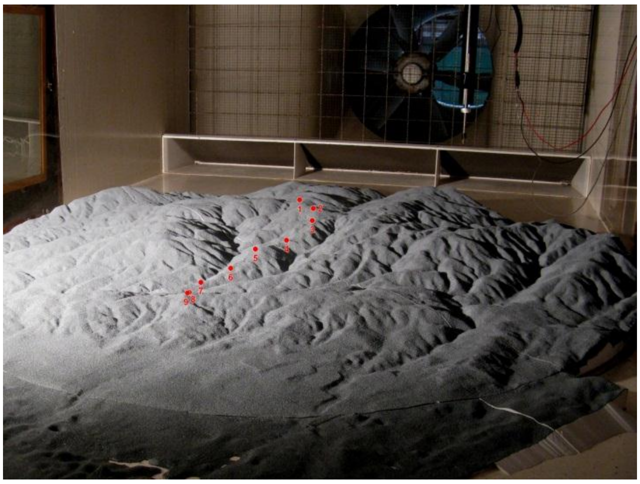

Figure 1. The hill model in the wind tunnel, seen from the northwest, showing the locations of the nine cup anemometers.

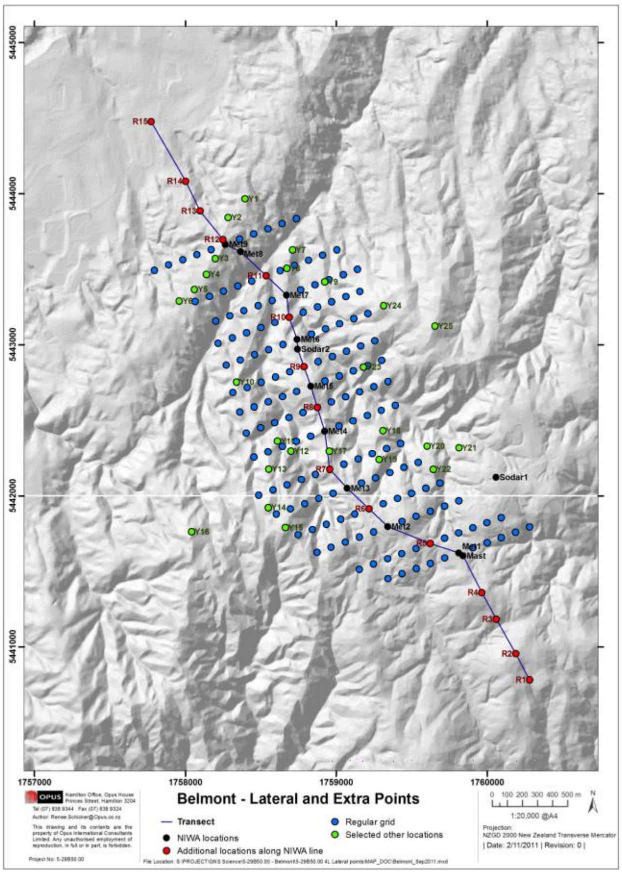

Figure 2. Plan of the wind tunnel measurement locations, including cup anemometer locations Met1 to Met9.

CFD analysis using Gerris

The modelling was done using the CFD code Gerris which has been developed and operated by NIWA. This uses a time varying, adaptive grid to solve the Navier Stokes equations, as described in Popinet, 2003. The topography was based on 5 m terrain contours, and the Gerris model resolution is 10 m in the vertical and 40 m in the horizontal 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 5 m at each cup anemometer location. The inflow condition was a wind from 345 degrees with a logarithmic vertical profile based on a roughness length of 20 mm and a speed of 20 m/s at 500 m – approximately Terrain Category 2 (AS/NZS 1170.2). 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.

Wind tunnel tests

The wind tunnel tests have been undertaken by Opus. A scale of 1:2000 was selected for the wind tunnel model. The choice of scale is a compromise between competing requirements. In general, a larger model scale is desirable for accuracy of positioning of the wind speed measuring equipment, and for aerodynamic simulation (e.g. Reynolds Number), while a smaller scale is desirable to be able to model a sufficiently large area around the test site, and to fit the model into the wind tunnel. The Opus wind tunnel turntable is 2.6 m in diameter, allowing a full-scale diameter of width of 5.2 km at the chosen scale of 1:2000. We decided that 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 height of the NIWA anemometer poles was 5 m, equivalent to 2.5 mm at 1:2000 scale. This was the lowest height above the surface that was measured in the wind tunnel study. The wind speed measurement probe was therefore very close to the model surface height, with potential influences due to height measurement error or model surface irregularities. We therefore considered that the measurements at 2.5 mm height had the possibility of being less consistent than the measurements at greater heights. This was one reason why a height of 10 m (5 mm) was selected for a regular grid of measurements, approximately 2.5 km long by 1 km wide, over the study area.

We obtained 5 m contour data of the study area from a 2011 aerial survey. The data was supplied by Greater Wellington Regional Council. Construction of the hill model was subcontracted to the model making company Human Dynamo Ltd. The model was made from high density white polystyrene foam. The use of a numerical milling machine enabled the model to be manufactured with impressively accurate hill contours.

We aimed to reproduce a Terrain Category 2 boundary layer simulation. After some experimentation, the surface roughness of the model that was selected for the study consisted of a dense coating of sand glued to the model surface (grade 20-30 standard sand, which has 0.7 mm typical grain size) covered with a single coat of paint. The wind tunnel mean speed was 12.0 m/s at 500 mm height

The wind speeds were measured using a single-wire hot film anemometer probe. This transducer is capable of measuring the wind speeds in either the X-Y, X-Z or Y-Z planes, but cannot measure the wind speeds in all 3 direction components. This is because the probe measures the component of wind speed normal to the wire, and essentially does not measure wind speed along the wire. (A similar limitation applies to cup anemometers, which only measure wind speeds in a horizontal plane.) Often a vertical wire orientation is used in wind tunnel studies (e.g. for pedestrian wind speed studies) so that wind speeds in the vertical direction are not measured. However, for the hill wind speeds study we decided to position the wire to measure in the X-Z plane; i.e. the probe was positioned with the wire horizontal, to measure the wind speeds blowing up and over the hills, but did not measure any component of wind speed across the wind tunnel. We anticipated that the Y component would be the smallest of the 3 components. To the extent that the measured wind speeds may be influenced by the limitation of the probe, the most likely effect is that measured wind speeds may be a little low in sheltered locations (e.g. in valleys) where there is high turbulence.

The wind speeds were recorded at 1000 Hz, typically for 1 minute at each location. Some selected locations, including the cup anemometer locations and the reference ABL measurements, were recorded for 2 minutes. The data logger was operated using 20 times oversampling to improve the signal quality. In the subsequent analysis, a 250 Hz moving average filter was applied to the recordings, which was equivalent to applying a 3-second moving average at full scale. This was calculated through equivalence of TV/L, where V_{model} = 7.4 m/s mean speed at 5 mm height, and V_{FS} = 20 m/s nominal mean speed at 10 m height.

The selected wind tunnel measurement locations included the following:

a) The locations of the nine NIWA 5 m high cup anemometers.
b) The two NIWA SODAR locations.
c) A permanent tall mast on the site.
d) Additional locations between the NIWA cup anemometers.
e) Additional locations to the north and to the south of the NIWA cup anemometers, in an approximate line along bearing 340. This line is approximately 4.4 km long, and includes 26 measurement locations.
f) 150 locations in a regular grid, measuring approximately 2.5 km long by 1 km wide, including all the NIWA cup anemometer locations.
g) Selected additional locations of interest.

Measurement locations in categories (a) to (e) were all measured at heights equivalent to full-scale heights of 5 m, 10 m, 20 m, 50 m, 100 m, 200 m, 500 m.

Measurement locations in categories (f) and (g) were measured at a single height equivalent to full-scale heights of 10 m.

All measurement locations were tested for wind direction 340. Locations in categories (a) (b) and (c) were also tested for directions 320 and 360. Linear interpolation was used to calculate the speeds for direction 345, for comparison with the site wind speed measurements and Gerris.

Figure 3 shows the measured gust hill shape multipliers for wind direction 340, with the wind shown blowing from the left in the plot. Note that this cross section is drawn through all the NIWA cup anemometer measurement locations (plus Sodar2) marked as black dots, plus additional locations selected by us marked as red dots. It is therefore not a section along a straight plan line. The x-axis in the plot is calculated as distances along a 340 degree bearing, with the model centre as the arbitrary zero.

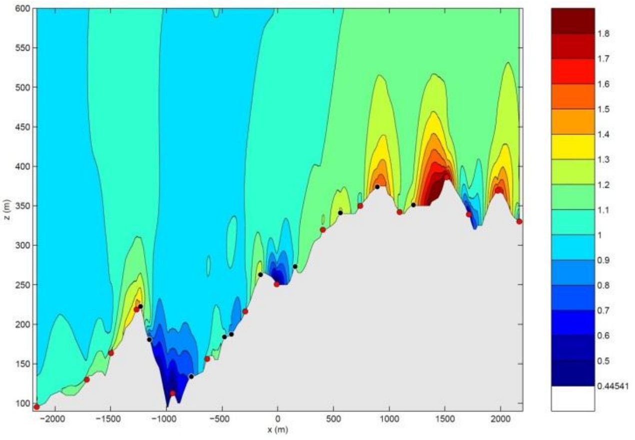

Figure 3. Cross section of the hill shape multipliers measured in the wind tunnel for wind direction 340. The wind is blowing from the left.

Figure 4 shows the mean and gust hill shape multipliers measured in the wind tunnel at 10m height for wind direction 340.

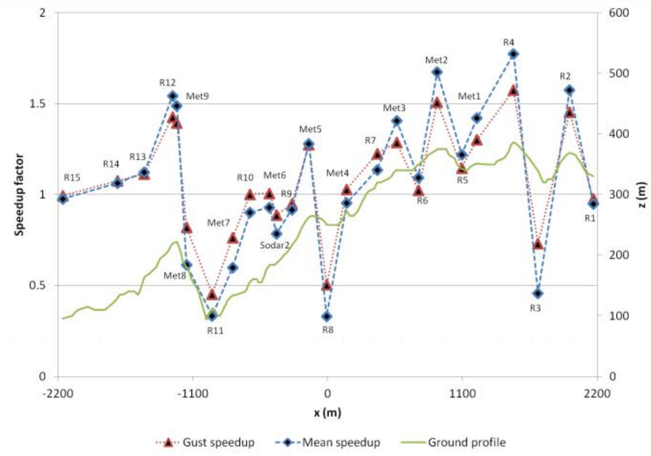

Figure 4. Wind tunnel mean and gust hill shape multipliers at 10m height for wind direction 340.

Figure 5 shows a plan of the gust hill shape multipliers measured in the wind tunnel for wind direction 340 at 10 m height, within the area of the regular grid.

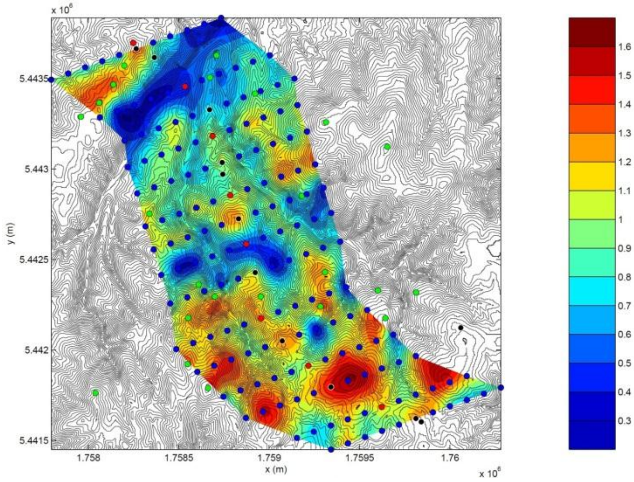

Figure 5. Plan of the gust hill shape multipliers measured in the wind tunnel for wind direction 340 at 10 m height, within the area of the regular grid.

Comparison of results

The results compared here are the hill shape multipliers for the nine anemometer locations Met1 to Met9 at 5 m above ground level for wind direction 345 degrees. The results from full-scale, the wind tunnel and Gerris are listed in table 1 for mean wind speeds, and in table 2 for gust wind speeds. Also listed are gust wind speeds calculated by NIWA using the computer program WASP developed by RISO in Denmark.

Met Anem	1	2	3	4	5	6	7	8	9
Full-scale	1.56	1.82	1.44	0.87	1.15	0.82	0.60	0.64	1.27
Gerris	1.26	1.68	1.36	0.94	1.19	0.84	0.65	0.57	1.26
Wind Tunnel	1.40	1.72	1.45	0.95	1.32	0.96	0.64	0.74	1.49

Table 1. Comparison of mean hill shape multipliers for the nine anemometer locations Met1 to Met9 at 5 m above ground level for wind direction 345 degrees.

Met Anem	1	2	3	4	5	6	7	8	9
Full-scale	1.46	1.66	1.35	1.05	1.25	1.00	0.84	0.81	1.31
Gerris	1.36	1.57	1.37	1.17	1.33	1.11	0.97	0.88	1.29
Wind Tunnel	1.33	1.56	1.34	1.07	1.31	1.04	0.80	0.93	1.44
WASP	1.26	1.72	1.26	0.85	1.47	1.03	0.74	1.15	1.72

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

These results show good agreement between the results for full-scale, Gerris and wind tunnel. The agreement for the WASP results is less good. The agreement between full-scale, Gerris and wind tunnel is apparently better for the gust hill shape multipliers than for the mean hill shape multipliers, for reasons which are not known. The agreement is also better for the anemometers with significant speedup over the hill (Anemometers 1,2,3,5,9) compared to the anemometers which have small speedup or are in more sheltered locations (Anemometers 4,6,7,8).

It appears that our best estimate of the true hill shape multipliers can be obtained by calculating the average of the results for full-scale, Gerris and wind tunnel. Table 3 lists the average of the hill shape multipliers using these three methods.

Met Anem	1	2	3	4	5	6	7	8	9
Mean	1.41	1.74	1.42	0.92	1.22	0.87	0.63	0.65	1.34
Gust	1.38	1.60	1.35	1.10	1.30	1.05	0.87	0.87	1.35

Table 3. Hill shape multipliers calculated from the average of the results for full-scale, Gerris and wind tunnel, for the nine anemometer locations Met1 to Met9 at 5 m above ground level for wind direction 345 degrees.

Hill shape multipliers calculated using AS/NZS1170.2

Gust hill shape multipliers calculations based on AS/NZS1170.2 have been done by NIWA and by the University of Auckland. NIWA have used a procedure that has been developed over many years, and codified in a spreadsheet. The University of Auckland have simply applied the procedure listed in AS/NZS1170.2, with two alternative approaches to the interpretation of the upwind contours. The first approach assumes that the hill starts at sea level. The second approach assumes that the valley between Met9 and Met6 can be interpreted as being flat for the purposes of applying AS/NZS1170.2. It should be noted that the UoA calculation has only considered the wind direction with the wind blowing along the line of anemometers. It has not considered the most adverse topographic cross-section within a 45 degree sector that is specified in AS/NZS1170.2.

Table 4 lists the gust hill shape multipliers calculated by NIWA and UoA. For comparison, it also includes the average of the hill shape multipliers from full-scale, Gerris and wind tunnel, reproduced from Table 3.

Met Anem	1	2	3	4	5	6	7	8	9
Av. of FS, Gerris & WT	1.38	1.60	1.35	1.10	1.30	1.05	0.87	0.87	1.35
NIWA	1.20	1.43	1.35	1.36	1.52	N/A	N/A	1.10	1.14
UoA sea flat	1.10	1.09	1.08	1.07	1.06	1.06	1.05	1.04	1.03
UoA valley flat	1.08	1.06	1.05	1.03	1.01	1.00	1.00	1.00	1.23

Table 4. Gust hill shape multipliers calculated by NIWA and UoA multipliers using AS/NZS1170.2 for the nine anemometer locations Met1 to Met9 at 5 m above ground level for wind direction 345 degrees.

It can be seen in table 4 that the UoA gust hill shape multipliers are rather close to each other, and are also rather small. The NIWA values are more variable, and are much larger. The UoA values are also much smaller than the hill shape multipliers from full-scale, Gerris and the wind tunnel.

It is with some concern one sees that it is very easy to obtain different values of wind speedup using the approach in the Loading Standard, when the calculation is done by different organisations. The UoA results also show that the same person may also get different results by making different but supposedly realistic assumptions.

Conclusions

Good agreement has been obtained between the results for full-scale wind speed measurements, CFD analysis using Gerris, and the wind tunnel study. Wind speed hill shape multipliers calculated using the Loading Standard AS/NZS1170.2 differed from the other procedures, and also differed markedly between the organisations using AS/NZS1170.2 .

It is clear that more work needs to be done on wind speed hill shape multipliers, and writing a codified method for determining the speedup in a consistent and conservative manner.

Acknowledgements

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