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Wind speed hill shape multipliers – wind tunnel study

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Abstract

A wind tunnel study has been done to measure wind speed hill shape multipliers for a hilly study area near Wellington, New Zealand. Wind speeds were measured in the wind tunnel for a range of heights and wind directions, at locations where cup anemometers have been installed on the hills. The aim of the research is to provide improved methods for structural designers to calculate design wind speeds for hilly sites.

Introduction

A programme of research has been undertaken by a consortium which includes NIWA, Opus Research, the University of Auckland and GNS Science. Wind speed hill shape multipliers have been measured in the field, and compared with computational fluid dynamic (CFD) computer modelling and wind tunnel testing. The aim of the research is to provide improved methods for structural designers to calculate design wind speeds for hilly sites, to reduce the vulnerability of the built infrastructure to wind damage through improved design wind speed procedures.

AS/NZS1170.2 provides a range of modification factors for calculating design wind speeds. It has been demonstrated (Flay et al, 2013) that, when building designers apply the calculation procedures to a complex hilly site such as the study site, the resulting calculated wind speeds can be substantially incorrect, or vary substantially depending on the interpretation of the designer. The hill shape multiplier can increase the wind pressure three fold over adjacent sites on flat terrain. For New Zealand's hilly and mountainous terrain, this puts the hill shape multiplier as being of primary importance when deriving wind actions.

On-site wind speed measurements were previously obtained at the same study site by NIWA in 2011 on 5 m tall masts (King et al, 2012). In 2013, additional on-site wind speed measurements were obtained by NIWA using taller 9 m masts, with some additional locations.

This paper discusses some results from the wind tunnel study.

Description of the study site

The study site is in the Belmont Hills, in the Wellington region of New Zealand, between the towns of Porirua and Lower Hutt, to the north of Wellington City. The location of the study site is shown in Figure 1. Figure 2 shows a plan of the study site including the measurement locations. Locations Met1 to Met9 were in the 2011 study, and locations Met10 and Met11 were added for the 2013 study. Figure 3 shows an aerial view of the site, and Figure 4 shows the wind tunnel model. Two photographs taken at locations in the study site are in Figures 5 and 6, which include a view of a NIWA 9 m tall mast with a cup anemometer and direction vane.

The topography consists of low flat ground close to sea level towards the northwest, rising through complex terrain to a maximum height of 382 m in an area of high ground towards the southeast, over a distance of about 4 km. The measurement locations are mostly located in a more or less straight line along a spur which rises up towards the southeast, along approximate bearing 150 – 330 degrees. To the northwest of the spur there is a ridgeline which runs in a more or less straight line across the line of the spur. The ridge bearing is approximately 040 – 220 degrees. There is a deep valley immediately behind the ridge, between the ridge and the spur. Measurement location Met9 is at the top of the ridge, at a ground height of 222 m, and measurement location Met 11 is at the top of the spur at a ground height of 381 m.

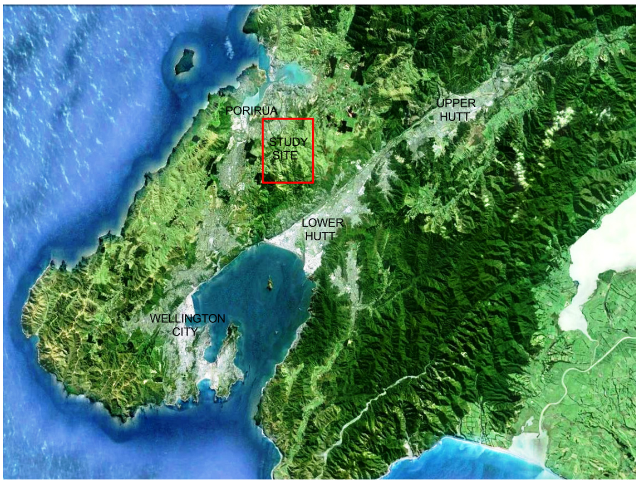

Figure 1. The Wellington region, showing the location of the Belmont hills study site.

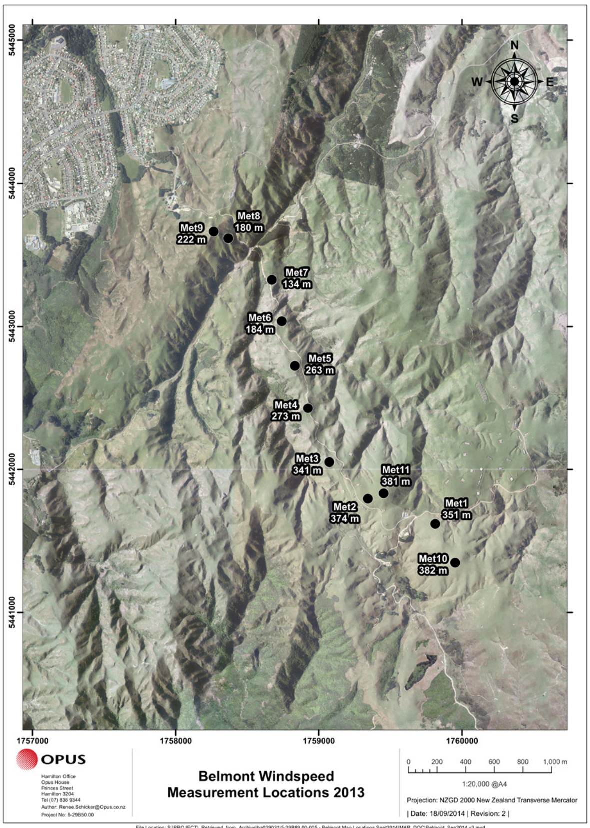

Figure 2. Plan of the study site, showing the measurement locations.

Figure 3. Aerial view of the Belmont hills looking towards the northwest, showing the measurement locations, with the town of Porirua and Porirua Harbour in the distance.

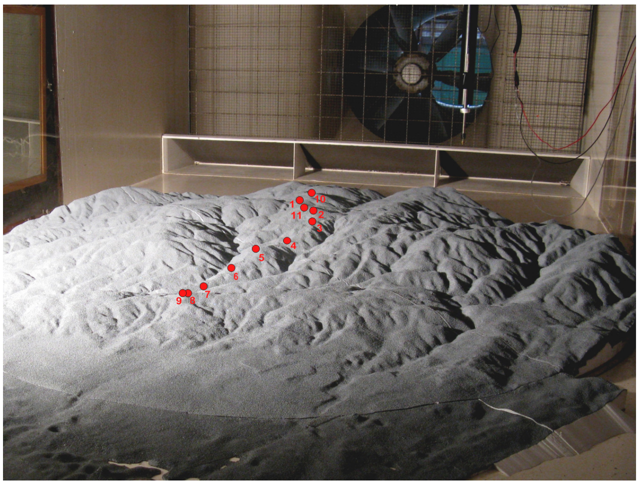

Figure 4. View of the 1:2000 scale wind tunnel model looking towards the southeast, showing the measurement locations.

Figure 5. A NIWA 9 m tall anemometer mast installed at location Met6, looking towards the northwest and location Met9 which is at the highest point on the skyline.

Wind tunnel test method

The wind tunnel study described in this paper was done in 2013 by Opus Research. A previous study using the same model was done in 2011 (Carpenter et al, 2011 and 2012). Both studies were done in the Opus Research Gracefield wind tunnel facility. A scale of 1:2000 was selected for the wind tunnel model, in order to be able to include an adequate area of model upwind of the site.

Figure 6. View from location Met10, looking towards the northwest. Location Met1 is at the tall mast in the centre of the photograph, and location Met11 is on the summit of the hill on the skyline left of centre, with the coast visible in the distance.

The lowest height above the surface that was measured in the wind tunnel study was 2.5 mm, equivalent to 5 m at the 1:2000 scale. A hotfilm probe with the wire mounted horizontally measured the wind speeds. The 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. In the 2011 study, there was some scatter in the measurements at the 5 m full scale height, and an improved method was used for the 2013 study, which has achieved more consistent measurements at that height. Therefore the 2013 measurements at 5 m height are preferred to the 2011 measurements. This highlights the complexities of obtaining and interpreting measurements at the 5 m height where the influences of local ground effects are greatest, and consequently the reasons why the height of the NIWA cup anemometers was increased from 5 m to 9 m for the 2013 measurements. It is pleasing that at heights greater than 5 m, the wind speeds measured in the wind tunnel are reasonably consistent between the 2011 and 2013 studies, typically within 2%.

We aimed to reproduce a Terrain Category 2 boundary layer simulation. 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 speeds were recorded at 1000 Hz for 2 minutes at each location. 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, corresponding to the averaging time of the NIWA cup anemometers. The gust speed was calculated as the mean speed + 3.7 standard deviations. Speedups were calculated by comparing the wind speed measured on the hill model to the wind speed measured on a flat surface at the same height above ground, and same location in the wind tunnel. The flat surface was prepared with the same painted sand surface as the hill model.

The wind tunnel testing was done for 8 northerly and northwesterly wind directions, at 10 degree increments between directions 310 and 020. Wind speeds were measured at 9 heights, corresponding to full scale heights of 5, 8, 10, 12, 20, 50, 100, 200, 500 metres.

Figure 7 is taken from the 2011 study, and shows the gust speed profile as a cross section through the site for wind direction 340. Location Met 9 is at the crest of the first ridge on the left site of the plot, and the highest two points in this cross section are locations Met2 and Met10. Location Met11 was not included in this cross section. The diagram is included here to show the hill cross section, and also to show how the wind speeds become more or less constant with increasing height at the peaks e.g. at location Met2.

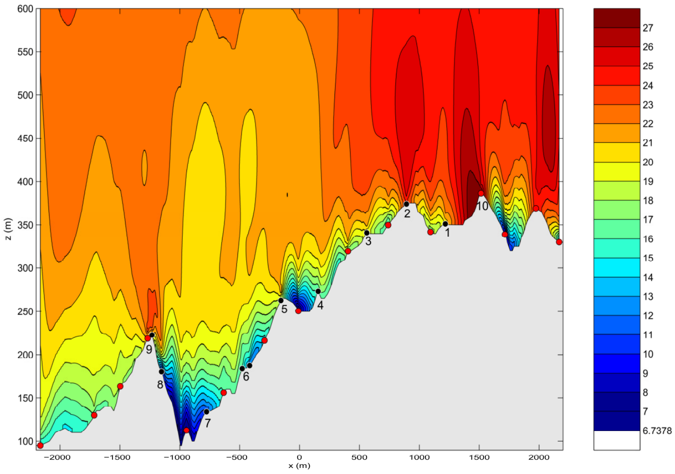

Figure 7.Cross section of gust wind speeds (from the 2011 study).

Results

Table 1 includes:

- The highest measured gust speedup at 10 m height for each location.
- The wind direction for the highest measured gust speedup.
- The corresponding mean speedup for that wind direction.
- Turbulence intensity (TI).
- The listed mean, standard deviation (Std) and gust speeds have been calculated from the measured mean and gust speedups, assuming a nominal mean wind speed of 10 m/s at 10 m height in a Terrain Category 2 boundary layer profile as described in AS/NZS 1170.2.

Location	Direction	Height (m)	Mean (m/s)	Std (m/s)	Gust (m/s)	TI	Mean Speedup	Gust Speedup
1	350	10	15.18	1.91	22.23	0.13	1.52	1.33
2	350	10	19.63	2.03	27.14	0.10	1.96	1.62
3	310	10	12.86	2.71	22.87	0.21	1.29	1.36
4	310	10	14.93	2.22	23.14	0.15	1.49	1.38
5	320	10	14.31	2.41	23.25	0.17	1.43	1.39
6	20	10	10.96	1.93	18.09	0.18	1.10	1.08
7	20	10	10.52	2.01	17.96	0.19	1.05	1.07
8	350	10	9.77	2.05	17.34	0.21	0.98	1.03
9	340	10	15.45	2.16	23.44	0.14	1.54	1.40
10	340	10	17.86	2.22	26.05	0.12	1.79	1.55
11	340	10	19.59	2.25	27.91	0.11	1.96	1.66

Table 1. List of maximum gust speedups measured in the study at each location, and the corresponding other wind speed measurements.

Figure 8 plots the mean and gust speedups from Table 1. In this paper we focus on locations 5, 9, 10, 11. In the order that these locations are seen by the approaching northwesterly wind, they are:

Location Met9 On the top of the ridgeline.
Location Met5 The first local peak on the spur, after the valley.
Location Met11 The summit of the spur
Location Met10 A second summit, downwind from Location 11.

Figures 9, 10, 11 and 12 show the measured speedups at 10 m height for these locations.

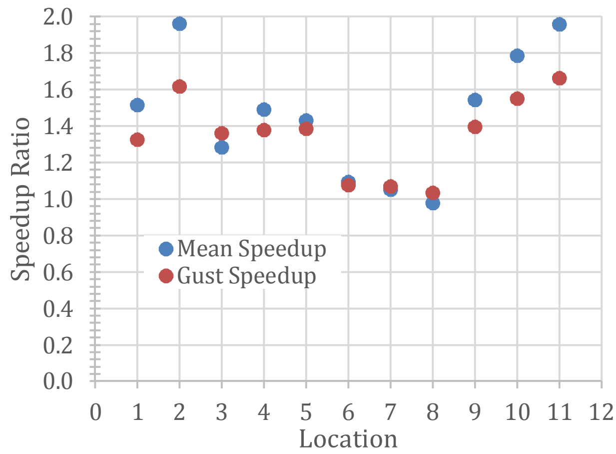

Figure 8. Plot of maximum gust speedup measured for each location, and the corresponding mean speedups.

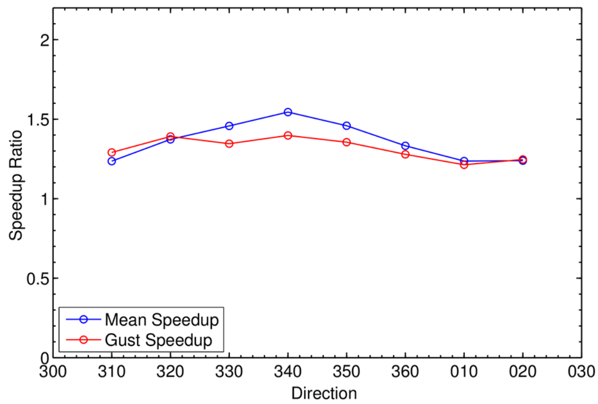

Figure 9. Wind speedup measurements for location Met9 at 10 m height.

Location Met9 is on a fairly simple ridgeline, and it might be expected to see the highest speedups occur for the wind blowing directly across the ridge for wind direction 310. In fact the gust speedup is fairly constant at around 1.3 to 1.4 over a range of directions, with a maximum gust speedup of 1.40 for wind direction 340. The mean speedup reaches a maximum of 1.54 for wind direction 340. We typically expect the mean speedup to be bigger than the gust speedup, but it can be seen that is not always the case: for wind direction 310 the gust speedup is bigger than the mean speedup.

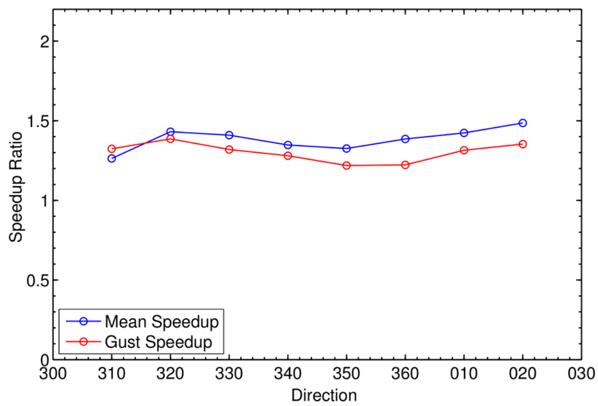

Figure 10. Wind speedup measurements for location Met5 at 10 m height.

At location Met5, both the mean and gust speedups are fairly constant over a wide range of wind directions. The gust speedup reaches a maximum of 1.39 for wind direction 320, while the mean speedup reaches a maximum of 1.49 for wind direction 020. Due to its location on the spur, it might be expected that the speedups would be greater with the wind blowing up the steeper slopes on each side of the spur, but this does not happen.

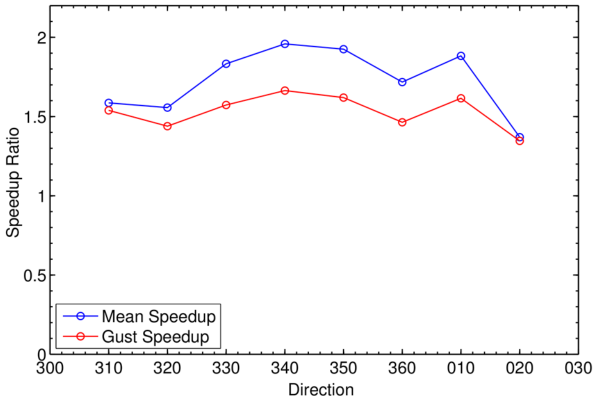

Figure 11. Wind speedup measurements for location Met11 at 10 m height.

Location Met 11 has the highest measured wind speeds. It is on top of a small hill on the spur, which is essentially at the summit of the test area. The highest gust speedups is 1.66 and the highest mean speedup is 1.96. Both were measured for wind direction 340. Similarly high wind speeds were measured over a range of directions between 330 and 010. This range of directions corresponds to the wind blowing approximately parallel to the line of the spur for direction 330, to the wind blowing at an angle of about 45 degrees to the line of the spur for direction 010. It is likely that a second spur to the west, running parallel to the test spur, provides some sheltering for the more westerly wind directions.

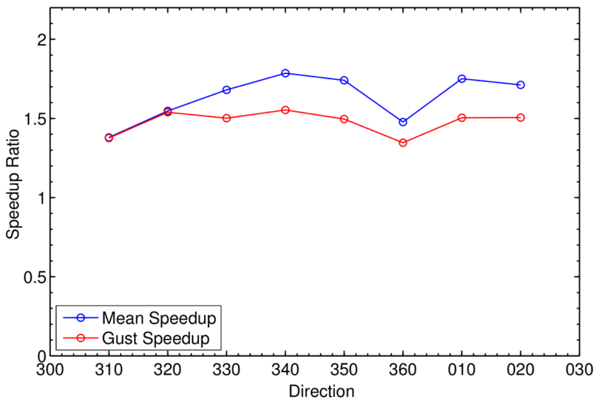

Figure 12. Wind speedup measurements for location Met10 at 10m height

Location Met10 is on a similar hill to location Met11, at the same elevation, but is a further 700 m to the southwest. The two hills are separated by a flattish area which is some 30 m lower. The pattern of wind the measured wind speeds is very similar to that at Met11. The main difference between the two locations is that the highest wind speeds at Met10 is some 8% less than the speeds at Met11. This is due to the sheltering at Met10 which is provided by the upwind hill at Met11.

A feature of the direction plots (Figures 9 to 12) is that the mean and gust speedups typically have similar values at direction 310, and also to a lesser extent at direction 020. This is because the upwind topography is more complex at these wind directions, particularly for direction 310 where the wind blows across the adjacent parallel spur. This produces some sheltering which reduces the mean wind speed, and causes increased turbulence which increases the gust speed. This therefore reduces the difference between the mean and gust speedup values.

Figure 13 shows the mean speedup and gust speedup profiles at measured at Met11 for wind direction 340, which includes the highest measured wind speeds at 10 m height as shown above. The figure shows that the speedup varies substantially with height, with the measured gust speedup reducing from 1.75 at 5 m height to 1.04 at 500 m height. However it should be noted that, combining the measured speedups with the initial Terrain Category 2 boundary layer profile over flat ground, the resulting wind speeds are more or less uniform over the full range of heights.

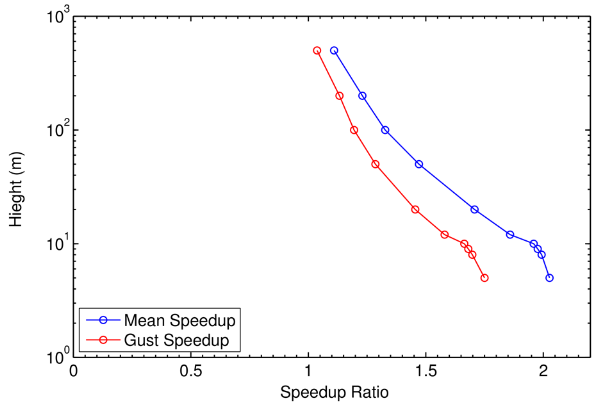

Figure 13. Wind speedup profile for location Met11 for direction 340.

At the locations with the highest wind speeds, such as Met11, the measured wind speeds are essentially constant between heights of 5 m and 10 m (~±2%), and then reduce only a little at greater heights (e.g. reducing by about 15% at 500 m). When plotted as speedup ratios, the effects of height appear substantial, but this is mainly due to the effect of the speed profile over flat ground.

The highest speedups measured in the study are:

Mean speedup: 2.17 at Met11, dir 350, height 5 m.
Gust speedup: 1.82 at Met11, dir 010, height 5 m.

Conclusions

The wind tunnel study has measured wind speeds at 11 locations on the Belmont Hills study site, at 9 heights for 8 wind directions at 10 degree intervals from 310 to 020 degrees. The range of directions covers the dominant wind directions experienced at the site. The highest measured wind speed multipliers were 2.17 for the mean speed and 1.82 for the gust speed, both measured at 5 m height above ground.

Acknowledgments

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