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Comparison of Wind Speed Hill-shape Multipliers Calculated by Seven Wind Loading Standards with Full-scale Measurements

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Abstract

This paper summarises and compares methods recommended in seven different national and international wind loadings standards for determining wind speed hill shape multipliers. In an attempt to help determine the accuracy of the predictions from the standards, a comparison has been made of the seven predictions from the standards and full-scale speed-up measurements over the rugged Belmont hills in the Wellington area of New Zealand. It was found that the hill-shape multipliers from all the standards were essentially similar. In comparison with the full-scale speed-up observations, none of the standards were found to provide adequate factors to account for changes in the wind sped over the complex Belmont Hill terrain example considered here. This result is influenced by the assumptions made to simplify the geometry into standard shapes considered in the standards.

Introduction

Much of New Zealand is covered in hilly, often mountainous, terrain and the wind flow over it is modified significantly by this terrain. These topographic effects on wind speed are recognised in the Australia/New Zealand Loadings Standard, AS/NZS 1170.2 (2011) – a reference document for the New Zealand Building Code which prescribes the minimum strength and stiffness of buildings in New Zealand.

In the Standard topographic enhancement is allowed for with a topographic multiplier, M_t, which is made up of a hill-shape multiplier ($1<M_h<1.71$), which depends on hill shape and steepness and the distance of the site from the hill crest, and a Lee Multiplier, M_{lee} to be applied within Lee Zones downwind of hill ridge lines. While the physical basis for including these effects is clear, the method by which these factors are calculated is unfortunately weak. This fact combined with some recent severe wind events, e.g. (Turner, 2014), (Kreft et al., 2011), and also the inclusion of winds as hazard in RiskScape (King and Bell, 2009) have caused renewed interest in wind engineering in NZ and a questioning of the guidance offered by the AS/NZS 1170.2 loadings standard.

Further details on the research are available in the final report on the research project, King et al. (2012), and aspects of the research have been presented in conference papers (Carpenter et al. 2012, Flay et al., 2013). Details of the comparison of the seven standards can be found in Nayyerloo et al. (2014).

Belmont Hill Speed-up Measurements

Belmont Hill Site and Instrumentation

The research project was focused on measurements and modelling of topographic speed-up effects within the Belmont Regional Park near Wellington. The area is typical of much New Zealand hill country (see Fig. 1) 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. 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 roughness classification of 2 (according to AS/NZS 1170.2), although the terrain perturbations (ridges and valleys) are much larger than the terrain roughness.

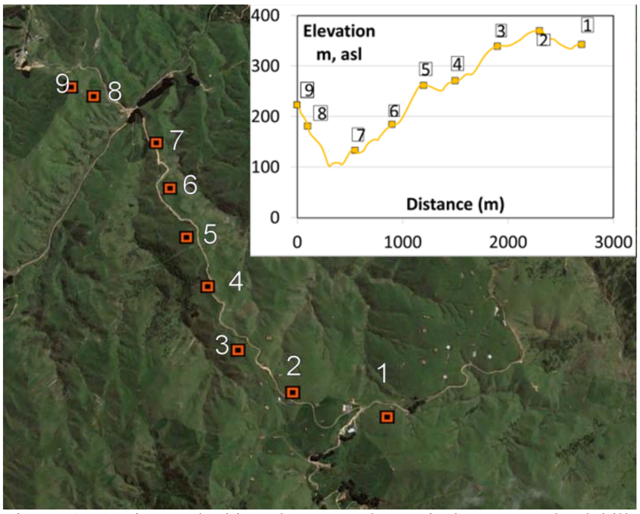

Figure 1. An image looking down on the typical New Zealand hill-country of Belmont Regional Park near Wellington, with locations and profile of heights for the instrumented masts.

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.

Full-scale Observations of Wind Speed-up

The paper focuses on the 18-hour observation period from 12 noon on 6 February, to 6 am on 7 February 2011 when the wind direction was approximately 345°. Fig. 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 intensities plus directions of average and maximum winds for this period were recorded.

In order to determine hill-shape multipliers based on these observations, an estimate of the wind speed at a 5 m elevation at a neighbouring site at a location not affected by the Belmont Hills was required. Data from Wellington Airport were used for this purpose (Carpenter and Reid, 1990). The speed-up results are shown in Fig. 3. Mast 2 is the most elevated and has the highest speed-up, whereas Masts 4, 6, 7 and 8 are sheltered behind ridges and have the lowest speed-ups, generally less than 1.0.

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 and anemometers is slightly to right of centre.

Description of the Methods used by the Loadings Standards to Estimate Wind Speed-up

AS/NZS 1170.2

It is rather difficult to apply the AS/NZS1170.2 speed-up procedure to Belmont Hill as it is based on 2-D hills, whereas the instrumented Belmont Hill is very 3-D. Furthermore, the full-scale measurements are along a ridge as shown in Figs. 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 (largest slope) for the topographic multiplier, requiring multiple contours through each point of interest. Further details of the approach are available in the Standard (AS/NZS1170.2:2011).

Calculations for the gust hill-shape multipliers were carried out for each of the mast locations using AS/NZS 1170.2, (2011) using the procedures outlined in the standard and its commentary, except that only the 345° wind direction was analysed, not the worst contour in upwind 22.5° arcs, as specified in the standard. Difficulties in dealing with the valley shown at top-left of Fig. 1, and near the top of Fig. 2 resulted in the calculations of two sets of predictions of wind speed-up. One set (sea flat) assumed that the "hill" started at the flat sea, and the other set (valley flat) 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. Mast 9 upwind of the valley was assumed to be on the crest of a hill starting at the sea.

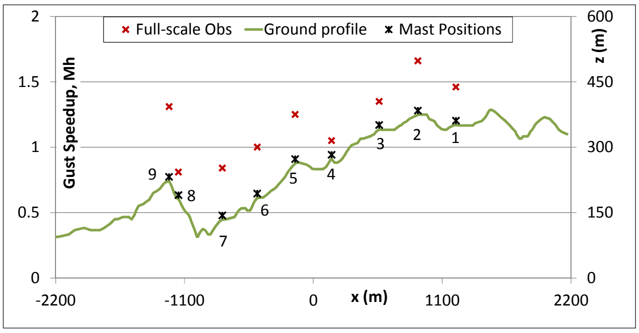

Figure 3. Ground profile and full-scale gust speed-up measurements for wind flowing from left to right.

ASCE/SE17-10:2010

The American Society of Civil Engineers (ASCE) recommends including the topographic effects on wind speed in the design by applying K_{zt} to the design pressure, where all of the following conditions are met (ASCE/SEI 7-10, 2010):

"…

1. The hill, ridge, or escarpment is isolated and unobstructed upwind by other similar topographic features of comparable height for 100 times the height of the topographic feature (100H) or 2 mi (3.22 km), whichever is less. This distance shall be measured horizontally from the point at which the height H of the hill, ridge, or escarpment is determined.
2. The hill, ridge, or escarpment protrudes above the height of upwind terrain features within a 2-mi (3.22-km) radius in any quadrant by a factor of two or more.
3. The structure is located as shown in Fig. 26.8-1 [not included herewith] in the upper one-half of a hill or ridge or near the crest of an escarpment.
4. $H/L_h \geq 0.02$
5. H is greater than or equal to 15 ft (4.5 m) for Exposure C and D and 60 ft (18 m) for Exposure B. "

BS EN 1991-1-4:2005+A1:2010

The British/Euro code recommends considering topographic wind speed-up effects in design where:

1. Topography increases wind velocity by more than 5%.
2. Average slope of the upwind terrain is more than 3˚. The upwind terrain may be considered up to a distance of 10 times the height of the isolated feature.

In this code, *co* (orography coefficient) is defined as mean wind speed at height z over mean speed above flat terrain and is calculated by a rather involved procedure given in the standard (EN 1991-1-4, 2005).

ISO 4354:2009

ISO 4354 by the International Organisation for Standardisation (ISO) defines two topographical multipliers for the mean ($k_{topog,m}$) and peak (k_{topog}) velocity speed-ups over small-scale features (ISO 4354, 2009). The multipliers are the ratios of peak or mean wind speed at height z above the feature over peak or mean wind speed at height z above the upwind flat ground. Topographic multipliers can be calculated from wind tunnel tests or numerical modelling and if not possible can be obtained using the recommended equations in the standard. V_{ref} is the maximum wind speed averaged over 3 s referenced to a height of 10 m over flat open country terrain and $V_{ref,m}$ is the maximum mean wind speed averaged over 10 minutes referenced to a height of 10 m over flat open country terrain (ISO 4354, 2009). The effect of large-scale features (orographic features) can be considered in a similar way. These orographic multipliers are best obtained from full-scale measurements or from numerical calculations. If such information is not available, these multipliers should be taken to have the value of 1.0.

National Building Code of Canada (NBCC 2005)

Speed-up over hills and escarpments is considered in the National Building Code of Canada (NBCC) by applying a factor to the reference wind pressure over flat terrain (NBCC, 2005). It applies to buildings on a hill or escarpment with a maximum slope greater than 1 in 10, particularly near a crest. The factor reduces with increasing height and increasing distance away from the crest.

Japanese Standard (AIJ, 2006)

The Japanese standard has a topography factor, which reflects the change of the mean wind speed that occurs as wind passes at right angles over escarpments or ridge-shaped topography. When the inclination is less that 7.5°, or the location is more than a certain distance from the crest, then the topography factor does not need to be considered. The user obtains the topography factor from tables on the basis of the slope and distance from the crest.

Korean Building Code (KBC: 2009)

Architectural Institute of Korea recommends using topographic wind speed multiplier (K_{zt}) from Equation (0305.5.3) of the code. As for other standards, the Korean topography factor is determined from an equation that uses the hill or escarpment slope and distance from the crest as the input arguments.

Comparison of Topographic Wind Speed Multipliers from the Loadings Standards with Full-scale Measurements

AS/NZS 1170.2

Speed-up estimates were made using the contour shown in Figs 1 and 3 as a basis and assumed that the crest was 386 m high. From this location, the upwind terrain was subdivided into 500 m long segments for a distance of 4500 m. Then the average slopes of straight line segments fitted to each section were determined. It was rather difficult to fit straight line segments to the contour, and that in the valley between the Met 5 and Met 9 locations, the slope changes from positive to negative, but cannot really be regarded as less than 0.05. It is clearly evident that at no 500 m segment over this contour region the slope is less than 0.05. Thus, it is difficult to determine where the hill starts, and this can lead to ambiguity. Two different assumptions were used, but gave similar results. These are shown in Fig. 4.

ASCE/SE17-10:2010

Since the Belmont Hill topography meets the criteria outlined in the ASCE standard, the topographic factors for the mast locations, can be calculated as follows. For Exposure Category C (open terrain with scattered obstructions having heights generally less than 9.1 m) and assuming the valley between Met 9 and Met 6 is flat, and that the hill has a 3D axisymmetric shape (μ=1.5, γ=4 and $K_1/(H/L_h)$ = 1.05), and H = 225 m and L_h = 750 m for Met9, and H = 161 m and L_h = 1300 m for Met 5 to Met 1, the topographic factors can be calculated following the procedure in the standard. As Fig. 4 shows, the resulting factors are slightly higher than those recommended by AS/NZS1170.2.

BS EN 1991-1-4:2005+A1:2010

Similar to AS/NZS1170.2, the effects of topographic features on wind speed can be ignored in the European standard where the average slope of the upwind terrain is less than 3° (~ 5%). As before, H = 225 m and L_u = 1500 m for Met 9 and H = 161 m and L_u = 2600 m for Met 5 to Met 1, and the orography factors (C_o) can be calculated following the procedure described in the standard. The results are plotted in Fig. 4. For Mast 9 the resulting topographic factor is slightly higher than that of AS/NZS1170.2 and is similar to the factor derived from ASCE. For the other masts the results are similar to AS/NZS1170.2 and slightly lower than those recommended by ASCE.

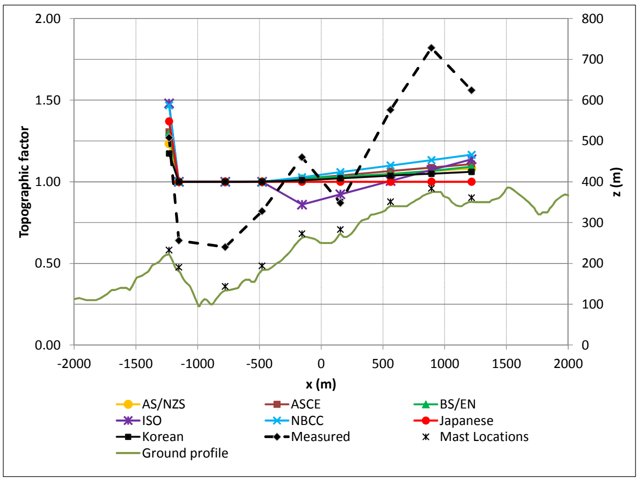

Figure 4. Belmont Hill topographic factors recommended by different standards

ISO 4354:2009

In the ISO 4354, similar to AS/NZS1170.2, for slopes less than 0.05, the topographic effects on wind speed can be ignored, for slopes between 0.05 and 0.3, some equations have been proposed to calculate topographic speed-up multipliers, and for slopes between 0.3 to 1.0, 0.3 is recommended to be taken as the effective slope to calculate the multipliers at or near the crest. Following the procedure outlined in the standard, mean topographic factors ($K_{topog,m}$) were calculated for three-dimensional axisymmetric hills and plotted in Fig. 4 For Met 5 and Met 4 that do not fall within k_2L_h metre of the crest, the resulting factors are less than 1.0. It is not clear from the standard whether these locations should be treated as "flat" with topographic factors equal to 1.0 or any factor that the equation yields is valid. The rate of increase in the resulting multipliers up the hill is slightly higher than those of the other standards reviewed but overall the multipliers are not much different.

National Building Code of Canada (NBCC 2005)

NBCC states that hills and escarpments with slopes less than 1 in 10 are unlikely to produce significant wind speed-up and implicitly recommends taking topographic factors equal to 1.0 in such situations. However, the resulting factors for Met 1 to Met 5 (slope = 0.06), from the NBCC equations described in Section 0, are higher than those recommended by the other standards reviewed herein. The Canadian standard also suggests a slope equal to 0.25 for any hills or escarpments steeper than 0.25. Other than these two points of difference, the NBCC adopts a similar approach to ISO to account for wind speed-ups over hills and escarpments. NBCC topographic factors are also plotted in Fig. 4.

Japanese Standard (AIJ, 2006)

In the Japanese standard for slopes less than 7.5˚ (~0.13) a topography factor of 1.0 is recommended, and for slopes greater than 60˚, the topography factor is assumed to be the same as that at 60°. For slopes in-between, some formulae are suggested. Only Met 9 is at a location which has an inclination (θ_s) greater than 7.5˚. Therefore, for the rest of the masts, $E_g = 1.0$. For Met 9, $H_s = 225$ m and $L_s = 750$ m, therefore $\theta_s = 8.5˚$. Met 9 is at the crest, therefore $X_s/H_s = 0$ and from Table A6.5 of the standard, by linear interpolation between the values of C_{1-3} for 7.5˚ and 15˚ in the table, $C_1 = 1.38$, $C_2 = 1.43$, and $C_3 = 0.17$, and Equation A6.5 of the standard yields $E_g = 1.37$.

Korean Building Code (KBC: 2009)

The procedure described in the Korean standard for calculating hill shape speed-up multipliers is slightly more complex than the other codes reviewed herein and includes wind turbulence intensity as well. Parameters involved in calculating the topographic factor, K_{zt}, can be determined by following the instructions of the standard. The exposure category is assumed to be exposed open terrain with few obstructions or scattered obstructions less than 1.5 m or grassland (i.e. Category D as per the Korean standard). Hence, $\alpha = 0.1$, $Z_g = 250$ m, and therefore $I_z = 0.18$ for $z = 5$ m. The resulting topographic factors are plotted in Fig. 4.

Conclusions

Procedures adopted by seven national and international standards to calculate wind speed-ups over hilly terrain were reviewed and compared for a section of the Belmont Hill as a typical example of New Zealand's hilly terrain. The overall aim was to understand best practice around the world regarding hill shape effects on design wind speeds to better inform any proposed changes to the current procedure adopted by the New Zealand wind loadings standard, for enhanced wind hazard resilience of New Zealand's built environment.

The following conclusions can be drawn from this review:

- While the physical basis for including topographic effects on design wind speed is clear, the method by which these factors are calculated in the standards reviewed, is unfortunately not clear, in particular, in terms of how the terrain geometry is simplified into the standard shapes for which the topographic factors can be calculated using the procedures adopted in the standards.
- The standards reviewed use similar approaches to estimate topographic effects with slight variations from one another. Therefore, the resulting factors are essentially similar.
- In comparison with the full-scale test speed-up factors, none of the standards provide adequate factors to account for changes in the wind speed over terrain with complex geometry as the Belmont Hill example considered here. This is influenced by the assumptions made to simplify the geometry into the standard shapes considered in the standards.
- The only code that allows for reducing design wind speeds over hilly terrain seems to be the ISO.

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