**Recent testing of Topographic Speed-Up Factors as used in Codes**
**Prepared for IASS WG4 Meeting in Toronto September 2022**
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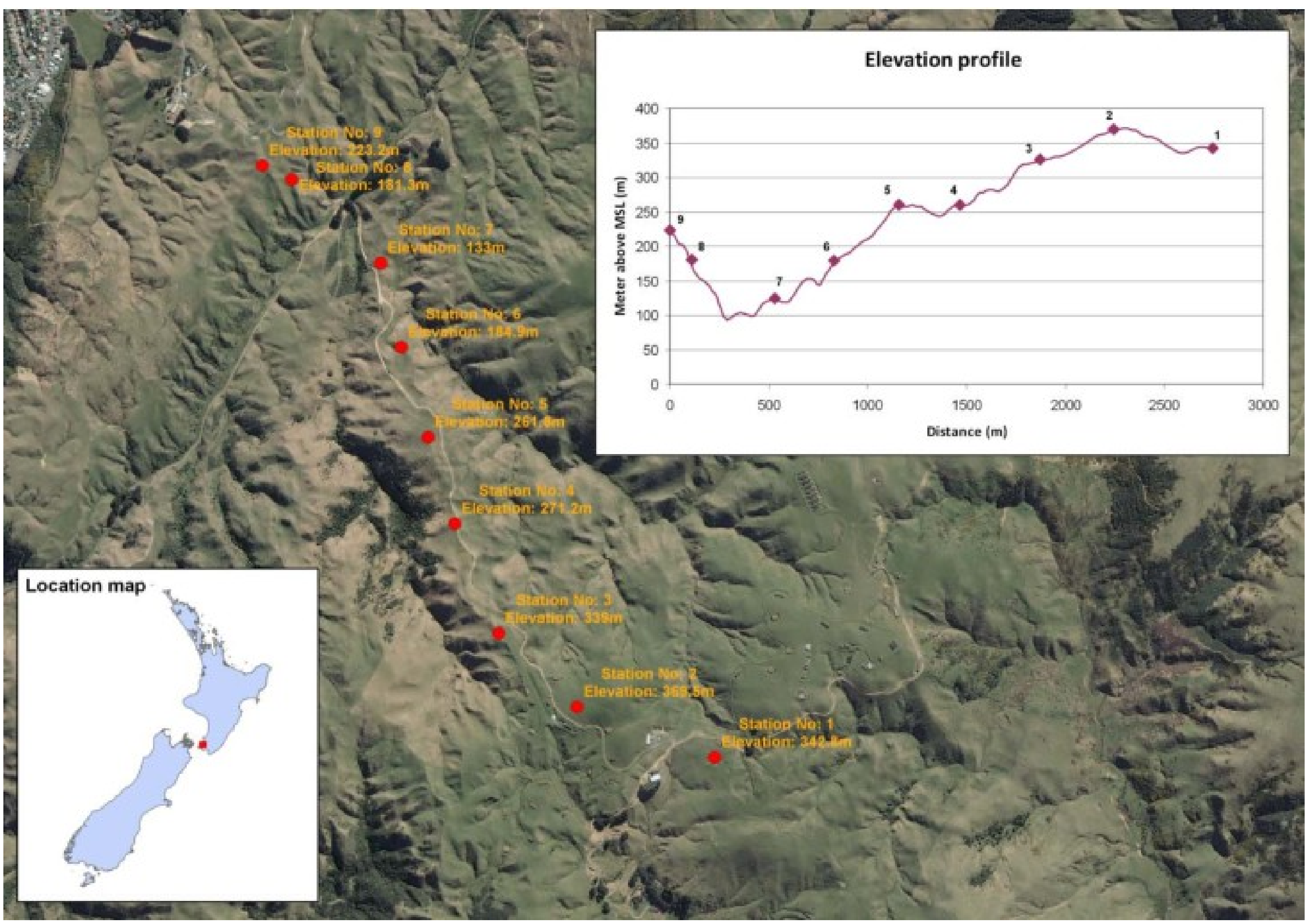
## 1 Topographic Speed Up in Rolling Terrain

Communication Towers are frequently located on elevated terrain, including mountain peaks. This requires that the engineer include the effects of wind speed-up on the calculation of potential extreme loads. A wind speed up of 75% produces an increase in the wind load which is 3 times that in the absence of the elevated feature. The Building Codes in a number of jurisdictions provide a prescription for calculating the effect of topographic features on the extreme wind speed.

However, very limited testing has been done on how well these prescriptions conform to reality. Recently, an experimental set up for measurement of wind speed-up by topography has been carried out by Australia in New Zealand (Comparison of Wind Speed Hill-shape Multipliers Calculated by Seven Wind Loading Standards with Full-scale Measurements R.G.J. Flay, M. Nayyerloo, A.B. King, M. Revell, 17th Australian Wind Engineering Society Workshop, 2015).

Wind instruments were placed at 9 locations along a series of hills (in the Belmont Park) as shown in the elevation plot below, and the data collected was analyzed to extract the speed-up factor compared to the incoming wind (from left to right along the range of hills).



The researchers then calculated the recommended speed-up factor by 7 Building Codes including ASCE 7 -10, NBCC 2005, ISO 4354, BS EN 1991, AS/NZS 1170.2, AIJ 2006, and KBC 2009.

The results are shown in the following figure reproduced from the paper. The black dashed line represents the speed-up (topographic factor) calculated from the measured maximum 3 second gust at each of the 9 stations during an 18 hour period of observation as a ratio to corresponding observations at the Welland airport. The data shows a speed-up for the first hill on the left (Met station 9), as well as station 5 and station 2 (the station number for each measuring station is shown in the inset of the topographic map above). The data also shows speed reductions at locations in between the hills.

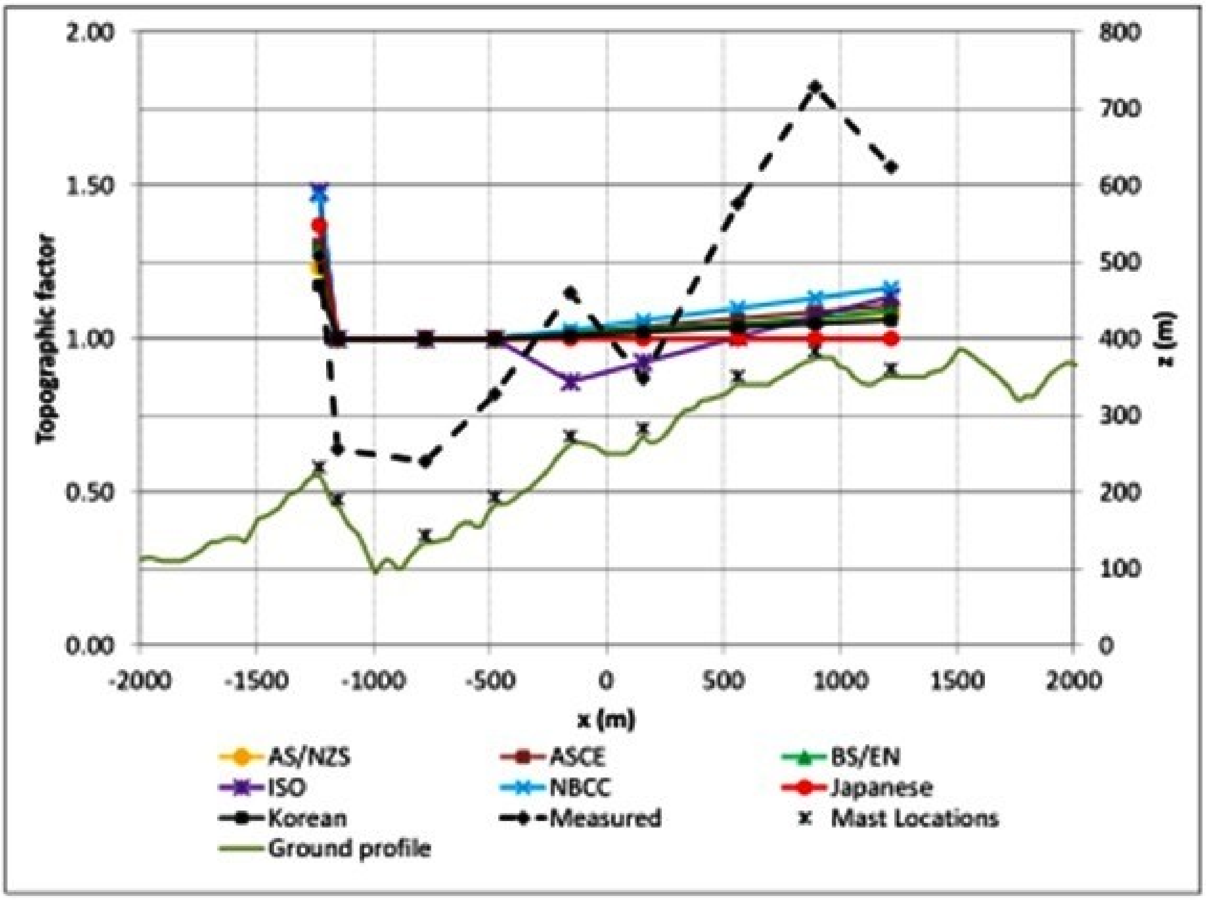



**Figure 4. Belmont Hill topographic factors recommended by different standards**

The code calculations for each of the codes (coloured lines and markers) listed in the Figure use the specific procedures for each code and the same airport observations to predict the expected speed-up. The code calculated values show a significant speed-up for station 9, and a small speed-up at station 2 for most of the codes.

The reason for the limited success of the ASCE 7 16, and NBCC, as well as the ISO and EURO codes is the fact that the codes present a methodology for the case of isolated hills and ridges, without any prescription for the more general and more common case of multiple hills and ridges in close proximity. The usual interpretation of the code wording by users seems to be that there is no speed-up effect on hills or ridges unless they exceed the average of the surrounding hill heights by a factor of 2 (TIA 222), or they are more than 2 miles from similar height features (ASCE 7 16).

In the latest version of ASCE 7 22, the first two criteria which restrict the speed up calculation to isolated topographic features have been dropped so that the ASCE 7 speed up shown in the figure above would now be different.

A subsequent study was carried out by modeling the Belmont Hills terrain in a wind tunnel, with measurements taken at a large number of locations in the wind tunnel (King, A.B.; Revell, M.; Carpenter, P.; Turner, R.; Cenek, P. and Flay, R. 2012. Modified wind speed due to topographic effects, *GNS Science Report* 2012/07. 34 p.) as well as CFD modelling of the speed-up.

A visualization of the wind-tunnel results is shown in the following figure. This shows the speed-up at the isolated hill, but also shows speed-ups at the smaller hills, which are in fact greater than at the isolated hill.

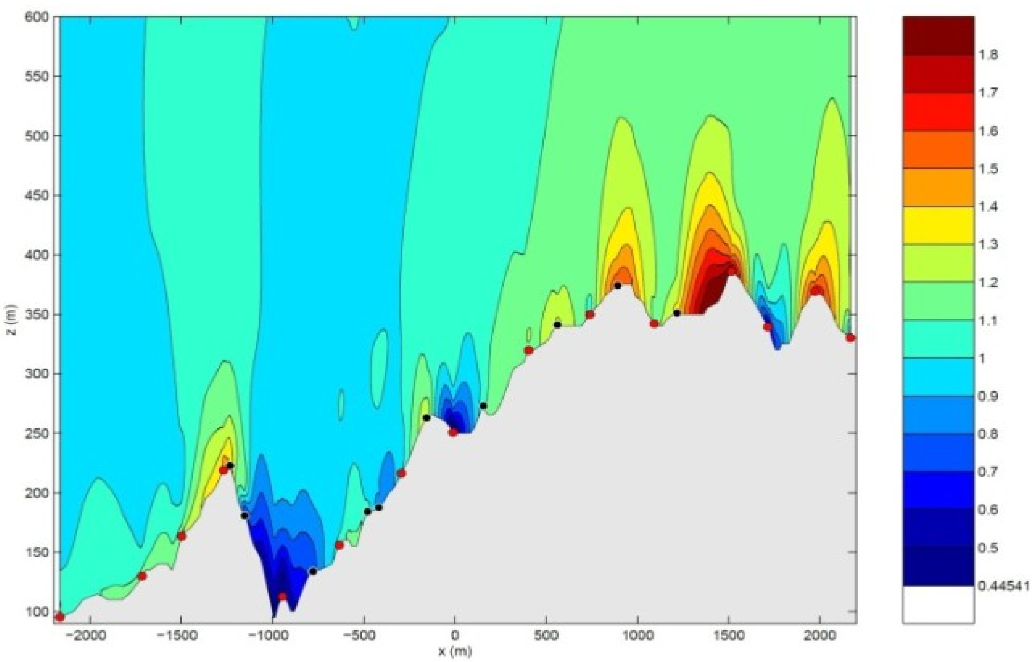
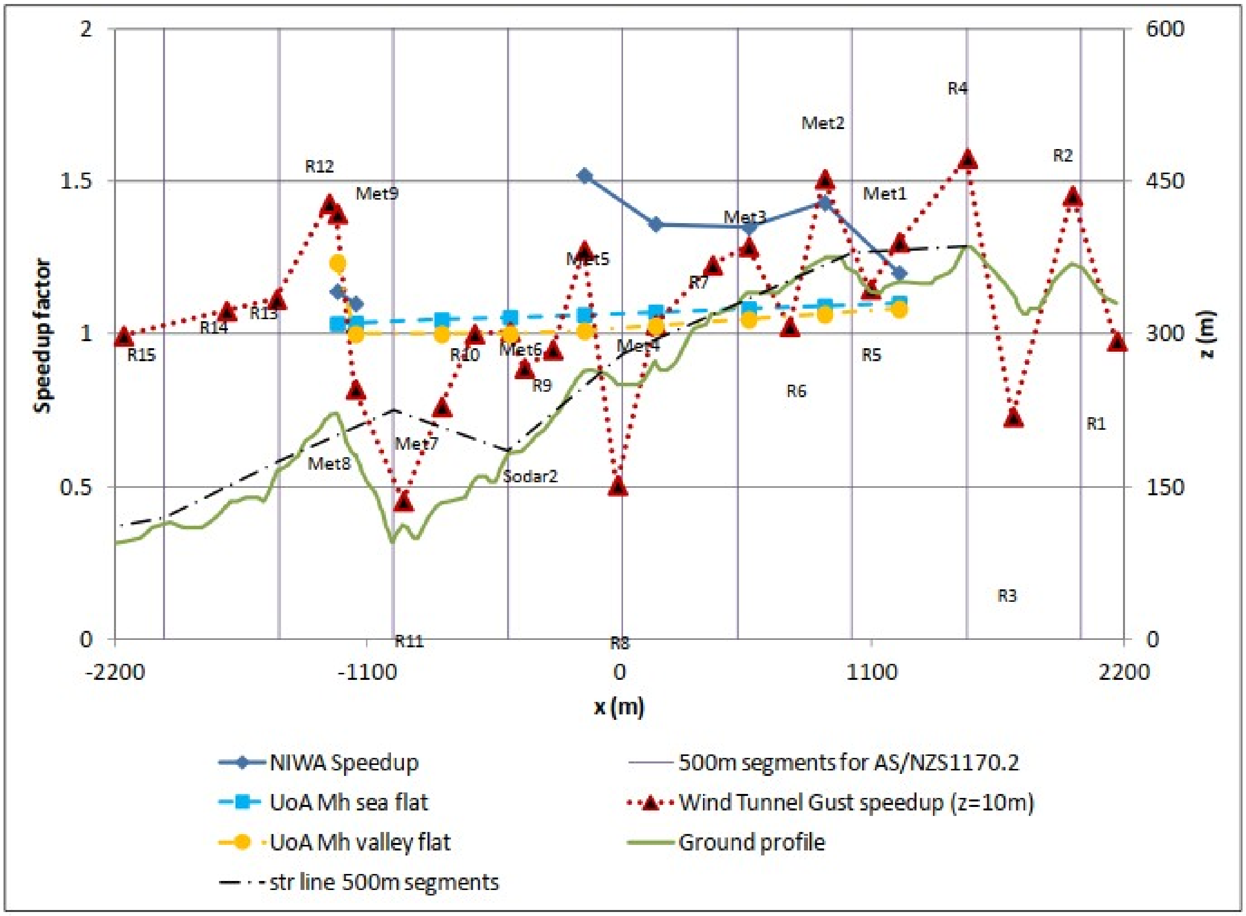



Figure 8 Cross section of the hill shape multipliers measured in the wind tunnel for wind direction 340. The wind is blowing from the left.

CFD modeling of the flow was then carried out on a dense grid of 40 m horizontal resolution and varying vertical resolution. The results of the modeling are extracted and analyzed for speed-up factor as shown in the following figure.




**CFD modeled Gust Speed Up for wind tunnel data**

This shows the speed up factor for gust speeds at 10m at the met sites of the field study as well as additional locations. Speed up factors of up to 1.6 are present for all of the major topographic features in a similar way to the wind tunnel and field studies. These model results are confirmed by the field measurements, and point to the need for additional guidance in the Building Codes for determining speed-up in the more general case.

The wind speed-up procedure provided in many of the Codes is based on the Taylor and Lee Simple Guidelines paper (Taylor, P.A. and R.J. Lee, 1984: Simple Guidelines for Estimating Wind Speed Variations Due to Small Scale Topographic Features. *Climatological Bulletin*, 18(2), 3-32) which interprets experimental data by use of theoretical work of J. Hunt.

The Guidelines include a prescription for dealing with multiple hills, so called rolling terrain, in a manner very similar to that for isolated hills. This prescription relies on numerical modeling analysis of the experimental data and shows that the usual speed-up formula can be used with parameters specific to rolling terrain in order to calculate the speed-up.

The ICE (International Climatic Evaluation Inc.) Site Specific procedures are based on the Taylor and Walmsley elaboration of the The Simple Guidelines ( Simple Guidelines for Estimating Wind Speed Variations due to Small-scale Topographic Features - An Update J.*L. Walmsley, P.A. Taylor, R. Salmon, Climatological Bulletin 1989)*

In the ICE procedures the continuous roughness and logarithmic profile description of the Planetary Boundary Layer is retained, which allows dealing with the effects of changes in roughness length on the wind profile; avoids the classification of roughness into 3 classes which creates numerous problems in analysis; and deals with topographic features such as hills, escarpments, ridges, and a succession of hills or ridges (rolling terrain).

In this formulation the adjustment for topography and terrain is written as an additive correction to the upwind profile incident on the topographic feature:

$$U_h(z) = \left(1 + D\,\Delta S(z)\right) U_{01}(z) + \Delta Ur(z)$$

where

$U_h(z)$ is the modified wind speed at the top of the feature
$U_{01}(z)$ is the profile at the bottom of the feature
$\Delta Ur(z)$ is the change in profile due to roughness change up the hill
$\Delta S(z)$ is the speed-up factor due to topography
D = (1 – 0.625x/L) for x < 2L is a correction for distance from the crest

here the speed-up is given by

$$\Delta S(z) = B\frac{H}{L}\exp\left(-A\frac{z}{L}\right)$$

where H is the hill height and L is half-width at half height as shown in the following figure.

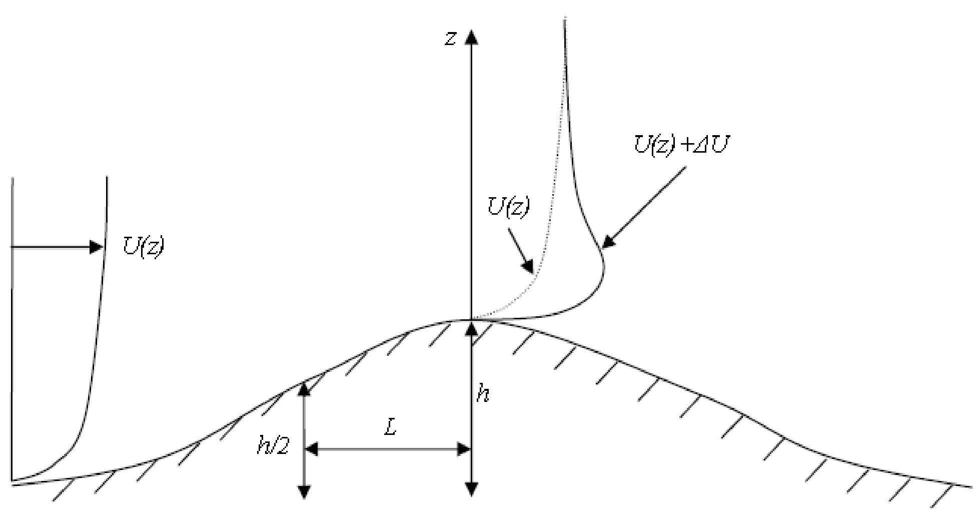



***Figure 2.6 – Development of wind profile over a hill***

The parameters A and B are specified as listed in the following Table 1.

*Table 1: Speed up parameters*

| Terrain Type | A | B |
|---|---|---|
| 2D Hill (ridge) | 3.0 | 2.0 |
| 3D Hill | 4.0 | 1.6 |
| 2D Escarpment | 2.5 | 0.8 |
| 2D Rolling Terrain | 3.5 | 1.55 |
| 3D Rolling Terrain | 4.4 | 1.1 |
| Flat Terrain | 0.0 | 0.0 |

The ICE procedure was used to model the wind speed-up detailed in the New Zealand experiment, using H and L parameters extracted from the elevation plot of the above Figure.

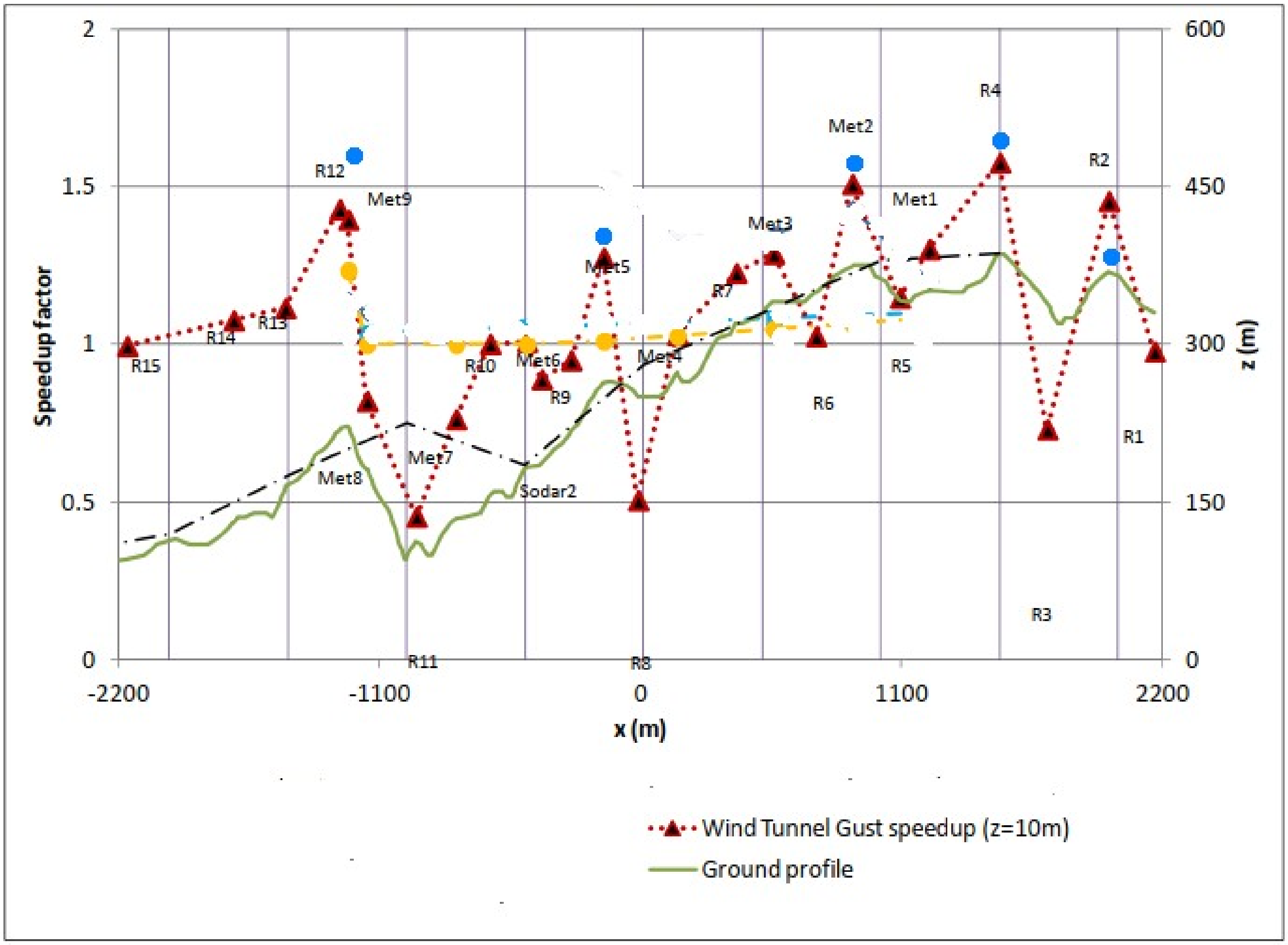
In the ICE procedure, no speed reduction is considered, although the procedure does calculate up to a 25% reduction in the sheltered valleys as per the D parameter.

Table 2 shows, the speed-up calculated using the ICE procedures for the main hills and ranges from 1.22 to 1.61 as a result of the hill slope and height, and on whether the feature is isolated or in rolling terrain. The incident wind speed profile is assumed to be the same for all hills as for the first isolated hill.

*Table 2: Speed up calculation using ICE Procedures*

| Location | H | L | Classification | Speed-up |
|---|---|---|---|---|
| M9 | 125 | 300 | Isolated Hill | 1.58 |
| M5 | 150 | 500 | 3D Rolling Terrain | 1.30 |
| M2 | 175 | 500 | 3D Rolling Terrain | 1.52 |
| R4 | 75 | 150 | 3D Rolling Terrain | 1.61 |
| R2 | 50 | 200 | 3D Rolling Terrain | 1.22 |

These values are superposed on the speed up Figure below and are shown as dark blue filled circles in at the Met sites Met9, Met5, Met2 and the model Receptor sites R4 and R2.



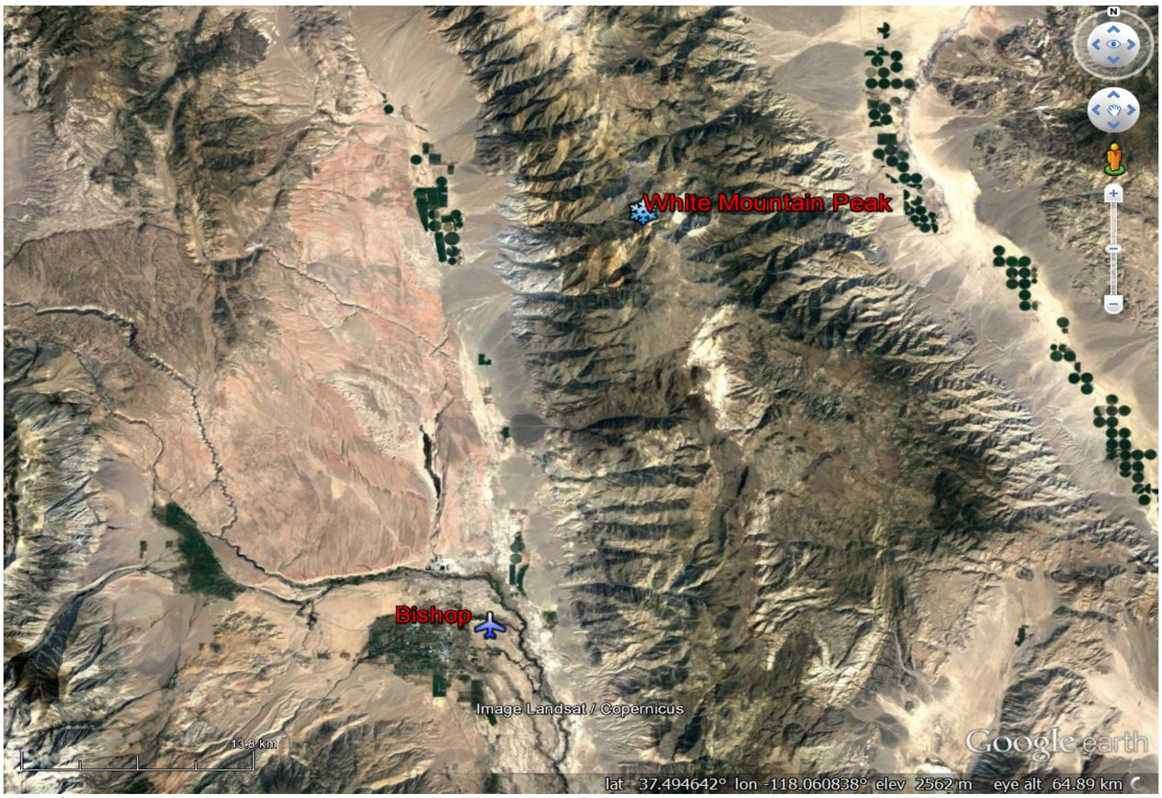

**ICE procedure speed-up calculation for the Belmont Hills**

The results show that the Code formulations could be modified to reproduce the observed speed-up effects for the case of rolling terrain. The usual prescription as in ASCE 7 22 for instance can be used but selecting the appropriate values for A and B to suit the situation. Thus if the hill at R4 location is treated as a Hill rather that rolling 3D, the speed up would be over-stated by 16% and hence the wind load would be over-stated by 35%.

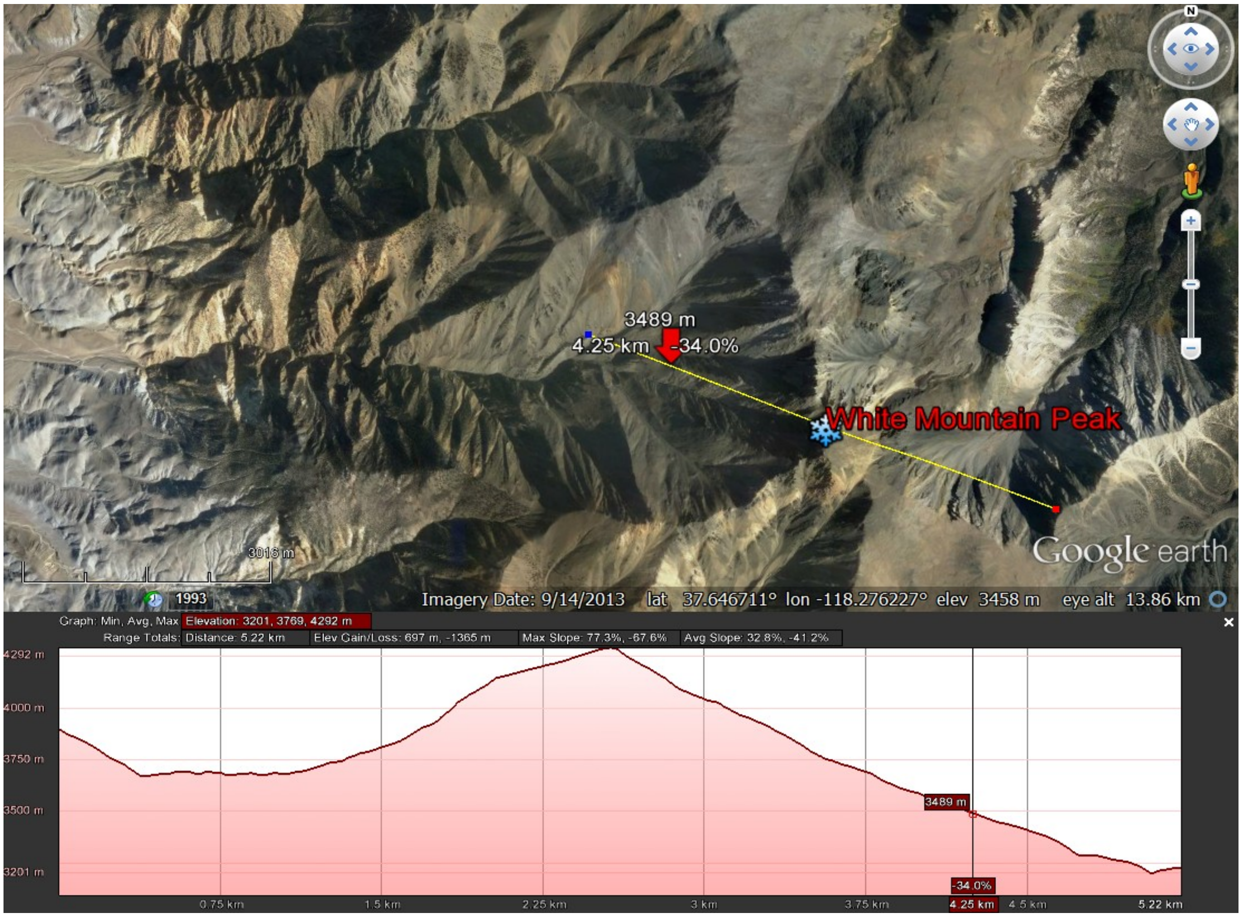
## 2 Using the speed-up correction for Mountainous Terrain

The other aspect of the speed-up prescription which has not been extensively tested is the applicability of the prescription to very high mountains and very steep slopes. The Simple Guidelines made clear that the basic data was collected for gentle hills and ridges which placed a limitation on the method to such situations. The codes do not set height limits on the terrain elevations, although there is a limit on the maximum slope that can be applied in the equations.

To address this question we applied the ICE procedures for a mountain range in California which has a climate station at the summit at 4300 m elevation collecting 3-sec gust data, and a suitable airport station at 1200 m elevation. The figure shows a map of the area, with White Mountain being the most prominent peak of a range of mountains of similar height.




The next figure shows the steepest slope aspect of the mountain, which shows the mountain being of height H = 1060 m and L =1100. In this direction the mountain is a 2D ridge. Since the H/L ratio in this case is greater than the 0.6 limit set by the procedure, the L is adjusted by the procedure to 1770 m in calculating the expected profile.

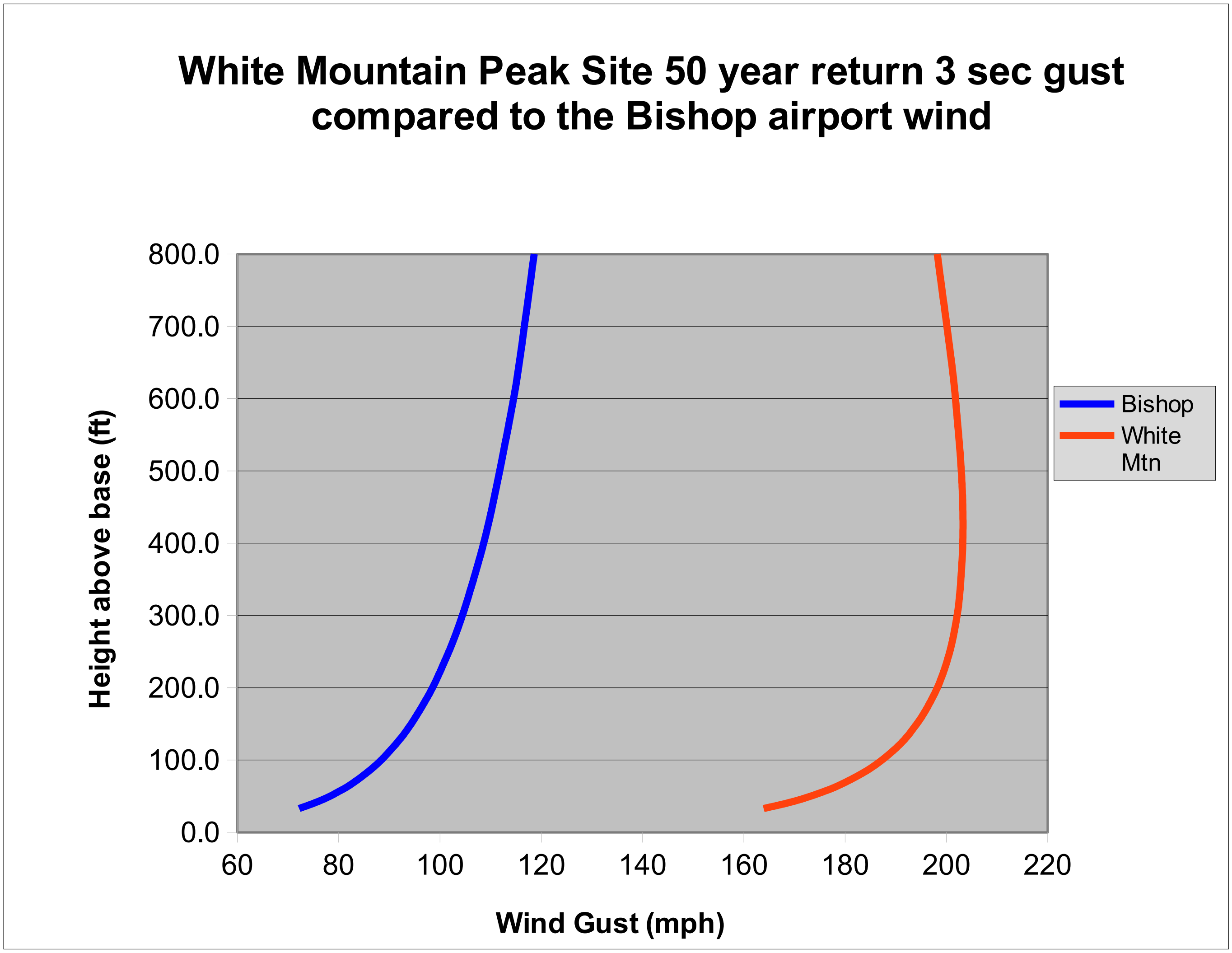



**Steepest slope aspect of White Mountain**

The profiles of 50 year return gust at the Bishop airport and at the summit are shown in the next figure.

The 50 yr return wind for Bishop airport was determined from 45 years of 3 sec gust data at the airport. This data was used to extract the monthly maximum gust, which forms a sample of 540 values which were statistically analyzed using the GEV statistical procedure to determine the 50 year return wind. Using the airport roughness information, a profile of the wind speed was determined, which shows a 50 year return value at 10 m elevation of 70 mph.

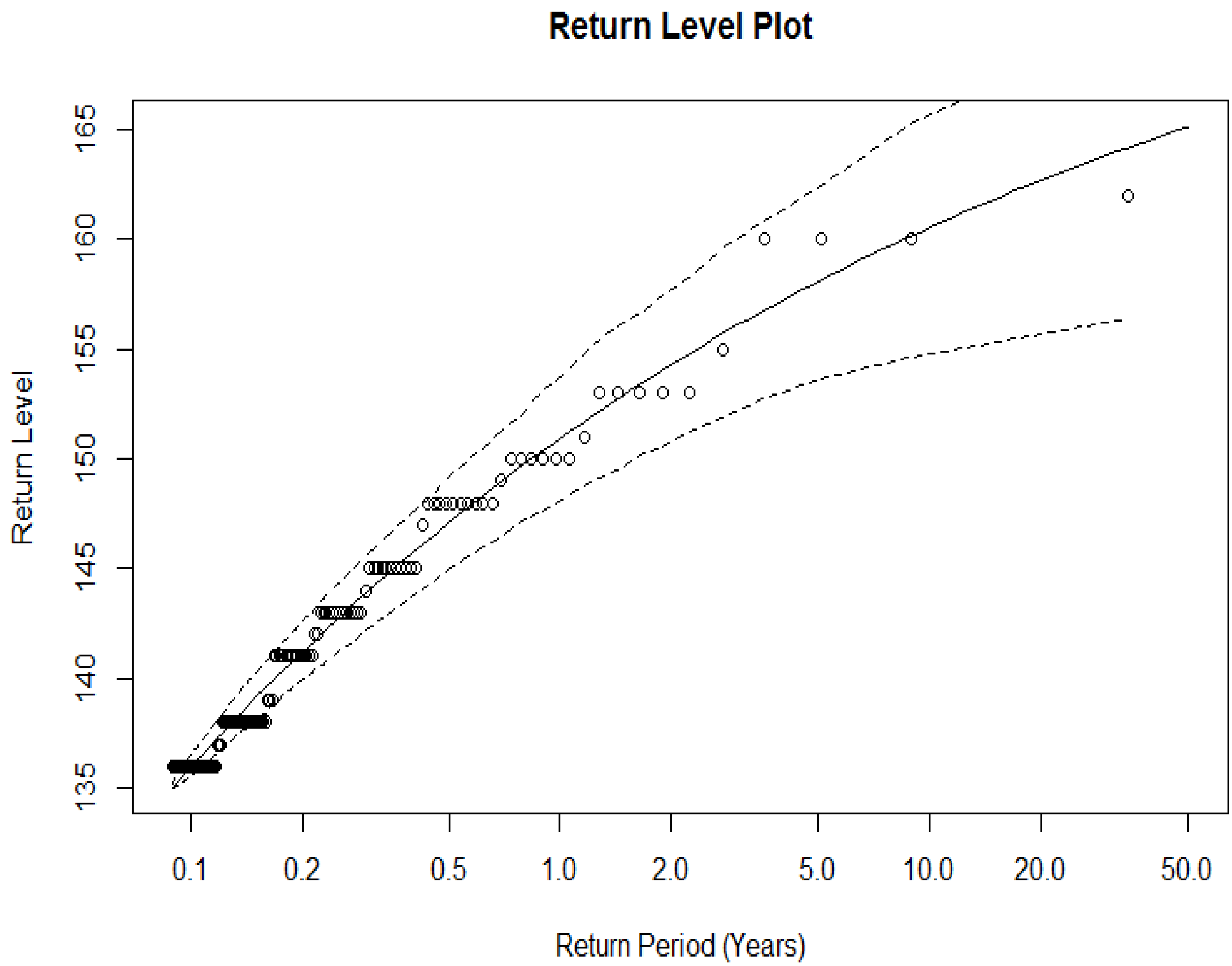
Based on the measured hill height and slope to the crest of White Mountain the speed up procedure predicts the 50 yr return gust on White Mountain of just over 160 mph. This includes the speed-up as well as roughness change on the mountain slope. The profile for the gust at White Mountain is determined by the ICE procedure and shows the typical speed-up bulge with the maximum being above 200 mph for heights above 200 ft elevation.




The gust data at the summit of White Mountain is available as a table displaying the frequency count of gust values in 2 mph bins which was analyzed using the GEV statistical distribution.

The following graph shows the return period plot for the measured gust data at the 10 m level. This shows a 50 year return gust of 165 mph which is similar to the 10 m elevation wind at the summit in the profile plot for the mountain site. As seen in the profile, the peak gust is about 200 mph at heights above 200 ft.

This shows that the Simple Guideline speed-up can provide reasonable predictions for very high hills and ridges as well as those which have steep slopes.




**Plot of the extreme tail of the wind gust distribution from White Mountain 3 sec gust data over a 30 year period. The extreme gust for a specified return period is plotted against the return period along with the 95% confidence bounds.**