THE VARIATION OF PEAK-GUST SPEEDS OVER AN ISOLATED HILL

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ABSTRACT

The derivation of the topographic velocity multipliers from the Australian and New Zealand Draft Building Codes is explained. Their values are shown to compare satisfactorily with the peak-gust factors obtained from wind-tunnel model studies for the case of a smooth, low isolated hill.

INTRODUCTION

The variation of the mean-wind speed over smooth isolated hills is now well understood and can be predicted with reasonable accuracy. However for rigid structures not susceptible to dynamic effects, the New Zealand Building Code (NZS 4203) along with many others, continues to use the quasi-static approach for predicting the maximum gust loading. This approach requires knowledge of the maximum peak-gust speed at the site.

Although there is a significant amount of data for mean-wind speeds over hills of various simple shapes, there are no data on the behaviour of peak-gust speeds. It is the intention of this paper to report on the behaviour of peak gusts over a hill by re-examining some model data files taken recently over an isolated model hill. This model with a slightly different surface roughness, had been used previously in several tests for the Askervein Hill Project. Askervein Hill is a smooth, oval hill situated on the exposed western coast of the Outer Hebrides. This hill has recently been the subject of intensive field and model wind-flow tests. Background details of this project are given by Taylor and Teunissen (1987). The results of this investigation will be compared with the peak-gust values defined in the new Draft Building Codes of New Zealand and Australia (DZ4203 and DR87163).

BACKGROUND THEORY

The extreme-value distribution of the peak-gust speed in a one hour recording has been analysed by Davenport (1964) for wind-loading applications. The approach is similar to the routine analysis of maximum annual mean-wind speeds. These are taken from one-year records and accumulated over a large number of years for the purposes of establishing annual-extreme wind speeds of various return periods. The analytical steps necessary to process the meteorological data are well described by Mayne (1979). In both applications, it is not the main body of wind-speed data that describes the probability of occurrence of peak-gust speeds, but the behaviour of the maximum (or minimum) gust speed of each recording. A large number of recordings is therefore necessary in order to obtain an accurate distribution of these extreme events. The probability of a peak-gust speed being less than $\hat{v}$ is given by

$$P(\hat{v}) = \exp[-\exp(-y)] \quad (1)$$

$$\text{where } y = a(\hat{v}-U). \quad (2)$$

The extreme value distribution is described by the values of the mode U (the most common value) and the dispersion 1/a (a measure of the spread). The mean value of the distribution is given by

$$(\hat{v})_{mean} = U+\gamma/a \quad \text{where } \gamma = 0.577. \quad (3)$$

$$\text{The variance} = 1.645/a^2. \quad (4)$$

The standard method of estimating these parameters is to take the peak-gust speed averaged over a short time period T_{av}, from each of a large number of independent recordings. Each recording should be taken over a recording period T_o, which is sufficiently long to establish an accurate value of the mean speed. The extreme values are ranked by magnitude and given a plotting position m in terms of the reduced variate y in equation 1. The extreme values are plotted on the ordinate against y to produce the straight line in equation 2. The estimate for y is given from the rank m by

$$y = -\ln[-\ln(m/(m_{max}+1))]. \quad (5)$$

This linear graph, $y = a(\hat{v}-U)$, provides values of U and 1/a from which the mean value and variance of the peak-gust speed may be calculated using equations 3 and 4. The distribution of peak-gust speeds is relatively narrow compared with the parent distribution and its variance decreases with increasing T_o.

The magnitude of the peak-gust speed recorded by an anemometer under specific wind conditions, depends on the distance constant of the instrument, the length of the recording and the averaging time adopted in the data acquisition process. In full scale measurements, the dynamic response of the anemometer can have a dominant effect on the magnitude of the peak gust recorded. Standard meteorological gust data are said to have an averaging time of about 3 seconds due to the apparent response time of the Dines anemometer. However this concept is misleading as the instrument response time is a function of the flow speed. In the wind-tunnel, the dynamic response of the hot-wire anemometer is normally well above the range of averaging times of interest to the engineer. By combining consecutive data points, a peak gust averaged over a certain averaging time, T_{av} can be obtained.

It is well established that the concept of a peak-gust speed averaged over a short time period is limited when applied to wind loading. The concept assumes that the area of influence or "size" of a typical gust, d_{gust} is related by Taylor's Hypothesis to the mean flow speed and the gust speed averaging time, T_{av} such that

$$d_{gust} \propto T_{av}.\bar{v}. \quad (6)$$

Greenway(1979) develops the use of the ratio, $d_{str}/^{x}L_v$ as a preferred alternative to the use of the averaging time, T_{av} for defining gust factors . The term d_{str} is a typical dimension of the structure and $^{x}L_v$ is the integral length scale of longitudinal turbulence.

The two approaches are linked together by Greenway through an empirical relationship giving the relevant averaging time for the measurement of extreme pressure loads on structures or structural elements of size, d_{str} as

$$T_{av} = 4.5\, d_{str}/\bar{v}. \quad (7)$$

With the use of equation 7, Greenway obtains an approximate estimate for the gust factor $G=\hat{v}/\bar{v}$, based on the 3 second average gust speed

$$G = 1+3.25(\sigma_v/\bar{v})[1-8x10^{-5}(\bar{v}.T_o/^{x}L_v)]. \quad (8)$$

Various empirical relationships have been proposed (ESDU 72026 (1972) and others) for the gust factor which is shown to depend predominantly on the averaging time T_{av}, the record length T_o and the turbulence intensity $\sigma_v/\bar{v}$. The proposed gust factors have a common form,

$$G = 1-A\log(T_{av}/T_o) \quad (9)$$

$$\text{where } A = a(\sigma_v/\bar{v})^n. \quad (10)$$

ESDU concluded that a=2.14 and n=1.33 but suggested that variations should be expected due to the subjective use of the averaging times allocated to the various field data used. Measurements by Bowen (1979) over an escarpment showed that a more simple relationship may be justified in view of the extent of these variations, and suggested

$$G = 1+(\sigma_v/\bar{v})\log(T_o/T_{av}). \quad (11)$$

Equation 11 may be compared with the empirical engineering relationship for the gust factor which is often quoted in terms of the peak factor g where

$$G = 1+g(\sigma_v/\bar{v}). \quad (12)$$

Deaves and Harris (1976) suggest a peak factor value of g=3.7 (for T_{av}=3, T_o=3600 seconds) which has been adopted by the New Zealand (DZ 4203) and Australian (DR 87163) Draft Building Codes. However Greenway's estimates are generally less than those given here which was attributed to the influence of the term $\bar{v}.T_o/^{x}L_v$ in equation 8.

Both Codes derive their topographic multipliers ($\bar{M}_t$ and $\hat{M}_t$) from fractional mean-wind speed estimates derived from Taylor and Lee (1984). The fractional mean-wind speed-up ΔS is defined as

$$\Delta S = (\bar{v}_h-\bar{v}_o)/\bar{v}_o. \quad (13)$$

The fractional mean wind speed-up over a simple hill was predicted analytically from the hill shape by Jackson and Hunt (1975) as

$$\Delta S = k_t.s.\phi. \quad (14)$$

In equations 13 and 14, $\bar{v}_h$ is the local mean wind speed over the hill; $\bar{v}_o$ is the mean wind speed at the same height upstream of the hill over open, flat terrain at the reference position; k_t is a topographic type factor, and s is a position factor (s=1 at the ridge crest). ϕ is the effective upwind slope of the hill defined as $H/2L_u$ where H is the hill height and L_u is the characteristic hill length or distance from the ridge to a level half the height below the crest in the direction of the wind.

The values of k_t adopted by the two Building Codes have slightly modified values from each other and from those proposed by Taylor and Lee (1984). The values from the NZ Code are listed below;

1.4 for escarpments, (Aust. Code, 1.6)

1.6 + 2.4(L_u/L_d) with a maximum of 4.0, for 2D ridges, and

1.4+36(ϕ_d-0.05) with a maximum of 3.2, for hills and ridges (Aust. Code, axisymmetric hills). (subscript u denotes upwind and d denotes downwind side of the hill).

It follows from equations 13 and 14, that

$$\bar{v}_h = \bar{v}_o+k_t.s.\phi.\bar{v}_o. \quad (15)$$

Both Codes use equation 12 over the hill as well as over flat terrain with the same value of g =3.7 in both situations. The implication is that the peak-gust speed is simply related to the turbulence intensity in the same manner over both types of terrain. The turbulence is also assumed to be convected over the hill without any change in the value of the rms velocity, so that

$$(\sigma_v)_h = (\sigma_v)_o = \sigma_v. \quad (16)$$

Based on these assumptions, it follows that over flat terrain;

$$G_o = \hat{v}_o/\bar{v}_o = 1+3.7(\sigma_v/\bar{v})_o \quad (17)$$

and over a hill;

$$G_h = \hat{v}_h/\bar{v}_h = 1+3.7(\sigma_v/\bar{v})_h. \quad (18)$$

It follows from equations 15, 17 and 18 that

$$\hat{v}_h = \bar{v}_o+k_t.s.\phi.\bar{v}_o+3.7\sigma_v = \hat{v}_o+k_t.s.\phi.\bar{v}_o$$

$$\text{and so, } \hat{v}_h/\hat{v}_o = 1+k_t.s.\phi/(\hat{v}_o/\bar{v}_o)$$

$$\text{and } \hat{M}_t = \hat{v}_h/\hat{v}_o = 1+k_t.s.\phi/(1+3.7(\sigma_v/\bar{v})_o) \quad (19)$$

Equation 19 is quoted in the commentary section of both Codes as the definition of the gust-speed topographic multiplier, $\hat{M}_t$. Similarly, equation 15 provides the mean-wind speed topographic multiplier

$$\bar{M}_t = \bar{v}_h/\bar{v}_o = 1+k_t.s.\phi = 1+\Delta S. \quad (20)$$

Note that $\bar{M}_t$ is related to the fractional mean wind speed-up ΔS, for which full scale and model data are already available from the literature reporting the Askervein Hill Project.

In order to compare the values of the Codes' gust-speed topographic multiplier $\hat{M}_t$, it may be related to the gust factors reported here by;

$$\hat{M}_t = \hat{v}_h/\hat{v}_o = (\hat{v}_h/\bar{v}_h)(\bar{v}_h/\bar{v}_o)/(\hat{v}_o/\bar{v}_o)$$

$$= G_h(1+\Delta S)/G_o. \quad (21)$$

MODEL TESTS AND DATA ANALYSIS

Askervein Hill has a relative height of about 116m above the surrounding flat terrain and a length along the ridge-line of about 2km. The characteristic length scale L_u of the hill in the direction of line A is 200m. The overall plan of the hill is shown in figure 1. The model data used in this paper were obtained from a recent wind-tunnel test on a 1:2500 scale model and are currently unpublished. The hill was tested at a single wind direction of 210° in a modelled boundary-layer of the same geometric scale as the model. The equivalent full-scale roughness length of the upwind boundary-layer and the model hill was 2.5cm compared with 3cm estimated from the full scale terrain. Previous tests on this hill model under similar conditions but with a modified surface roughness, have been reported by Teunissen et al (1987). This reference provides further details of the hill and surrounding terrain, together with mean wind and turbulence data.

The horizontal flow speeds measured in the turbulent boundary-layer at a number of representative positions over the model hill were recorded at high frequency (8kHz) using a horizontal split-film anemometer. The incoming data were filtered at 2kHz. The test positions were located over the hill along line A as shown in figure 1. Only the measurements taken at a height of 4mm (10m full scale) above local ground level are considered here. At each measurement position, the data recording was sufficiently long to divide into 8 independent records of equal length, each representing just over 10 minutes in the full scale. A time scale of 1/833 was used which was based on the model scale and the wind-tunnel test speed in order to simulate neutrally-stable, high wind conditions in the full scale. Using the method described earlier for the analysis of extreme values, the peak-gust speeds in each of the 8 records were ranked and plotted in terms of the reduced variate y to obtain the mean peak-gust speed at that location. Using the same raw data, consecutive data points were combined and averaged to obtain a range of full-scale averaging times from 0.3 to 20 seconds. The analysis was then repeated to obtain the mean peak-gust speeds over this range of averaging times at each location.

Only the gust factors at 10m over the surface of the hill obtained by considering the mean peak-gust speeds averaged over a full scale averaging time T_{av}=2.5s, are shown in figure 2a. The maximum peak-gust speed recorded at each position at the 8kz sampling frequency (T_s=0.1s full scale), are also presented to represent the upper limit. The third set represents the gust factors estimated from equation 12 with g=3.7 and using local values of turbulence intensity derived from the model tests.

DISCUSSION

All three estimates of peak-gust factor G_h, at a constant 10m above the hill surface (figure 2a), behave in a similar manner to the variation of the turbulence intensity. The empirical gust factors derived from equation 12 lie within the envelope set by the maximum recorded and the average 2.5s values. The choice of averaging time is of course, a fundamental parameter when recording these factors. The 2.5s averaging time was chosen to be close to the traditional 3s gust-speed and, also to represent a typical averaging time that may be more applicable to wind engineering applications than the maximum peak value recorded. (Using equation 7, if T_{av}=2.5s, $\bar{v}$=30m/s, then d_{str}=17m.) It is acknowledged however that its relationship with the traditional 3s gust-speed remains unclear (Greenway 1979). The effects of averaging time, turbulence intensity and the changing flow conditions over the hill will be the subject of further study and are not considered further in this paper.

Values of the mean velocity topographical multiplier $\bar{M}_t$, were obtained from other model studies of the same hill model by Bowen and Calvert (1986) and are shown in figure 2b. Close agreement between model and field results for $\bar{M}_t$ is evident except in the lee of the hill where the model failed to produce the separated flow that was apparent in the full-scale data. The problems associated with using small scale hill models are discussed further by Teunissen et al (1987).

The ratio G_h/G_o is utilised in equation 21 for estimating the experimental values of the peak-gust topographical multiplier $\hat{M}_t$ over the hill for a comparison with the code values. Normalising by G_o considerably reduces the overall effect from the choice of averaging time. Resulting estimates for $\hat{M}_t$ are given in figure 2c for both the time intervals considered. The gust-speed multipliers are significantly lower than the mean-speed multipliers as expected due to the terrain affecting mainly the mean speed and convecting the turbulence over the hill largely unchanged.

The topographic multipliers obtained from the Codes were chosen by using the following data for the hill shape;

Hill height h=116m.
Characteristic length L_u=L_d=200m.
Effective hill slope ϕ=h/2L_u=0.29 along line A, so ϕ=0.26 for the 210° wind direction.
Surface roughness category 2
(Roughness length z_o=0.03m)

The Code values presented in figure 2 were obtained from the 'detailed procedure' sections of both Codes. It is evident that within the tolerances created by differences in the Code rules, both Codes predict satisfactory values for M_t and M_t for this hill example. The along-wind variation is also seen to be quite adequate. However it should be remembered that the code rules were originally derived from sources close to the Askervein Hill data so that agreement for the $\bar{M}_t$ values should be expected. However it is encouraging to see agreement also in the values of the peak-gust terrain multiplier $\hat{M}_t$. Multipliers derived from the 'simple procedures' in both Codes provide significantly lower values than those presented here ($\hat{M}_t$=1.4 at the crest) and can therefore no longer be considered as conservative. However for most common building situations within suburbia, these values may well be satisfactory.

CONCLUSIONS

The values indicated by the New Zealand and Australian Draft Building Codes for the variation in mean-wind and peak-gust speeds over a low isolated hill were compared with recently obtained wind-tunnel model test data. Despite the common origins of the topographic multipliers in the Code rules, subsequent alterations have produced some differences between the Codes. However both Codes appeared adequate for the example considered.

Further work is necessary to check the Code rules against model and field data derived from a wide range of complex terrain and flow conditions. Further attention is also required to investigate the fundamental problem of defining a suitable gust factor. A better understanding must be sought to relate the techniques used in model and full scale data collection to the information required for dynamic structural design analysis.

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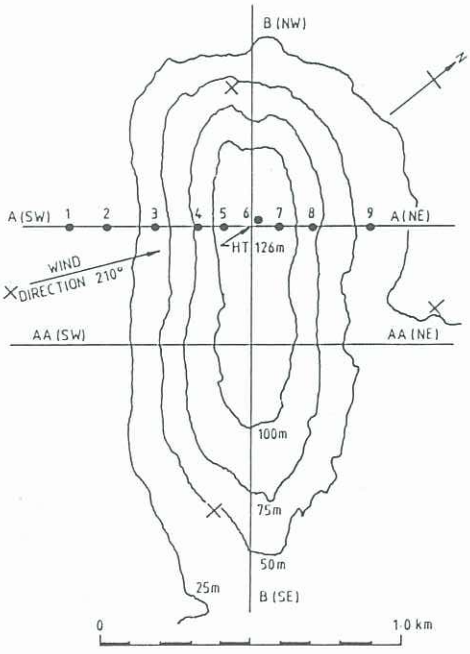

Figure 1. Contour map of Askervein Hill showing measurement positions and wind direction of the model tests.

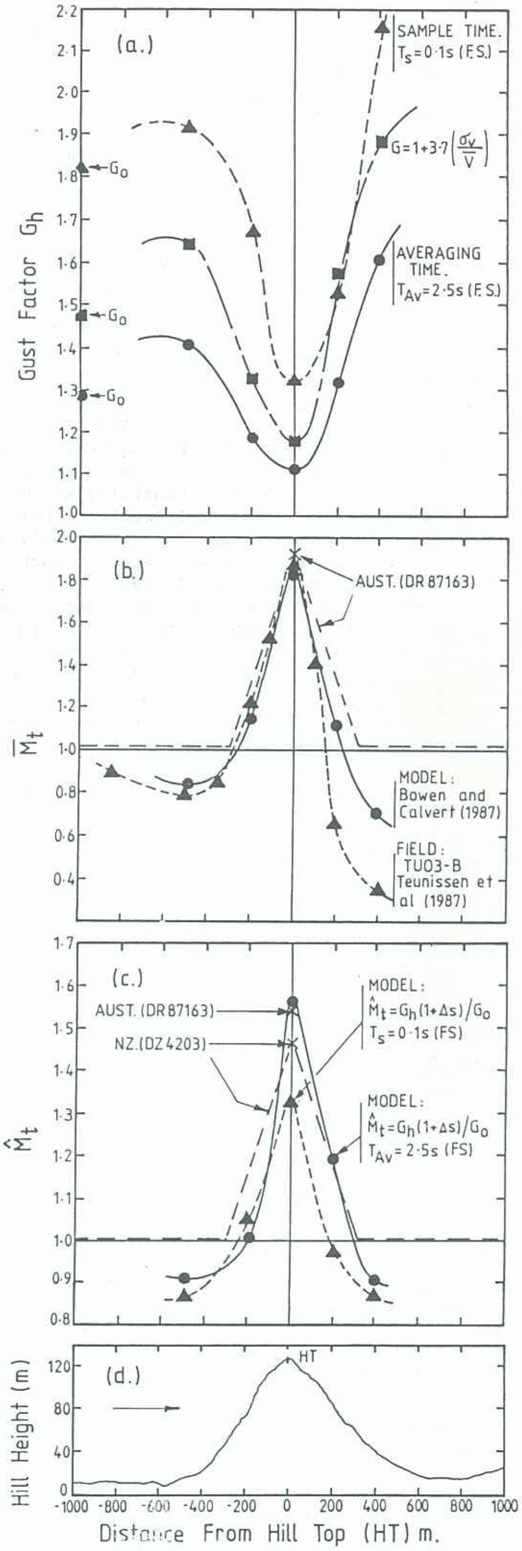

Figure 2a Various estimates of the gust factors measured over the model hill, G_h and far upstream, G_o.

Figure 2b Experimental and Code predictions of the mean-wind speed topographic multiplier $\bar{M}_t$.

Figure 2c Experimental and Code predictions of the peak-gust topographic multiplier $\hat{M}_t$.

Figure 2d Hill profile along measurement positions with stretched vertical scale. Wind flow from the left.