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Use of a penultimate method and OEN mixture model in the context of Wellington wind climate: some observations

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ABSTRACT

The variation of wind speeds with risk level is important for designers as it sets the amount by which the loads are increased to achieve the required safety margin. This variation can be described using the dimensionless characteristic product. The recent draft revision of AS/NZ 1170.2 proposes a characteristic product for Wellington higher than in the current version of AS/NZS1170.2. This article presents a perspective on extreme value analysis based on a penultimate extreme value method, XIMIS, which does not rely on the convergence assumption. The results show how an improvement to the fit, consistent with the Weibull-shape parameter, results in higher characteristic product. The improved fit results in load factors 4-8% less conversative than for the draft revision. The article concludes that the inaccuracy associated with the convergence assumption should be considered in the context of Wellington wind climate. It also presents an initial attempt to use the Offset Ellipse Normal mixture model in the context of Wellington, identifying 5 different possible wind mechanisms.

1. Introduction

The location of Wellington in the Roaring Forties combined with the impact of topography makes Wellington one the of the windiest city in New-Zealand. While the design of most building structures in the city remains governed by earthquake actions, the cladding design including glass or secondary structure design is typically driven by wind pressures. Design wind speeds are an essential feature of any building wind loading assessment and in the case of Wellington tend to generate very high design wind pressures. This article provides a perspective on the wind climate statistical analysis based on penultimate extreme value methods and presents the result of an initial attempt to use the relatively recent Offset Ellipse Normal mixture model to review the potential complex wind mechanisms affecting the Wellington region.

2. Preamble

The design wind speeds for the Wellington Region are given in the current version of the Australian/New Zealand Standard (2011) for Wind Loading AS/NZS 1170.2:2011 for Return Periods (RP) ranging from 1 to 10,000 years. In the case of Wellington, the plot of the design wind speeds squared, V^2, against the reduced variate y (Equation 1 below) is shown to be close to a straight line, which is the representation of the conventional asymptotic Fisher-Tippett Type I (FT1) model for annual maxima. This model is defined by its mode U and the dispersion 1/a. The dispersion is of particular interest for designers as it determines the amount by which the loads vary for different risks of exceedance. In other countries where Ultimate Limit State (ULS) wind speeds are not made explicit, this value is used to set the load safety factors applied to the characteristic wind loads (usually 25 or 50-year RP wind speed). For comparison purposes, instead of the dispersion, the dimensionless characteristic product noted π (=aU) is often used to characterize this variation as below:

$$y = a(V - U) \quad or \quad \frac{V}{U} = \frac{y}{aU} + 1 \tag{1}$$

with y: reduced variate =ln(-ln(P)), with P probability, 1/a: dispersion, U: mode, π (=aU): characteristic product.

As per Cook (1985), π can also be shown to be the product of the Weibull shape parameter, w, of the Parent wind distribution and the yearly number of independent storms. Updated design wind speeds were proposed in the recent draft revision of AS/NZ 1170.2 (Australian/New Zealand Standard (2020)). In addition of the change in design wind speeds, it is interesting to note the change in the characteristic product, π. As in Allsop (2011), a fit was derived based on the new design wind speeds, resulting again in a good fit to a FT1 model for a value of π equal to 7.13. Such a high value of π would suggest either a significant number of independent events and/or a Weibull shape parameter relatively high. Extreme wind speeds analyses are typically carried out using asymptotic distributions, such as the FT1 asymptotic distribution which are convenient models to approximate the exact distribution Φ. The linearization required to approximate Φ with the asymptotic model introduces an error which is minimum when the Weibull shape parameter, w, is equal to 1 but could increase as w increases. As the new value for the characteristic product, π, suggests a higher w shape parameter, the convergence error may also increase. This observation has motivated the study presented below.

3. Extreme Value Analysis

3.1 General

Methods to derive extreme wind speeds, such as those of AS/NZS1170.2, vary and are still the subject of debates between wind engineers. Most methods rely on the assumption of convergence mentioned above, inevitably introducing an error in the wind speed estimation. The observed data is forced to fit a model which may not be exact. Due to the possible larger w Weibull shape parameter inferred by the characteristic product in the draft revision, this error may be more pronounced in the case of Wellington. In the author's knowledge, only the penultimate extreme value method as summarized by Cook (2014) does not rely on the assumption of convergence and is therefore the method selected for the analysis below. Cook (2014) provided a very comprehensive background and framework for its implementation. The implementation of the XIMIS penultimate extreme value method developed by Harris (2009) is used. Only a short summary is provided below. The following equation for the reduced variable y was given as the FT1 penultimate distribution:

$$y = \exp\left(-\exp\left(-\left(\frac{V^w - U^w}{C^w}\right)\right)\right) \tag{2}$$

For XIMIS, Harris (2009) gave positions and the weights used in the least square method to provide a bias-free minimum-variance fit to the observed data.

3.2 Wind Speed Time-Histories

The data used in the analysis below are the time-histories of the mean and 3s-gust wind speeds recorded at Wellington Airport and Frontlead over a 25-year period for Wellington Airport and 11 years for Frontlead. The data was checked for general homogeneity. While some irregularities were noted, the time-history for the mean speed was generally found suitable for the analysis. More irregularities were observed for the gust speed time-histories and only the last 7 years of the dataset was retained, which is considered a minimum for the Extreme Value Analysis using sub-annual data. The wind speed data used in the analysis were corrected for roughness exposure using the ESDU (1974), to be consistent with Open-Country terrain (z_0=0.02) exposure and at 10m height. For comparison with the wind speed from the AS/NZS1170.2, the mean wind speeds are further factored by the gust factor equal to 1.62. The 3s-gust speeds are corrected to an open-country 1s-gust speed using ESDU and increased by 3% to be consistent with the 0.2s-gust definition standard. If the anemometer was previously found to be a 3-cup anemometer, the gust speed would require a further correction as in Holmes (2012) and results below may be unconservative. In this exercise, the focus is deliberately on the dimensionless characteristic product rather than absolute wind speeds - although these are still given for information.

3.4 XIMIS Preliminary V^2-Fit

Peak wind speeds are extracted from the time-history using the same methodology of the Method of Independent Storm as in Cook (1982). The peak wind speeds were squared and plotted according to the expected mean positions of the ranked wind speeds as per XIMIS method. The choice of using squared wind speeds means that w in Equation 2 is set equal to a value of 2 and the fit is made on two parameters only. The 5-95% confidence interval is plotted as dashed lines using the Bootstrap methods as per Cook (2004). The following remarks on the fit shown in Figure 1 can be made. The plot exhibits a noticeable upward concave curvature, suggesting a larger shape parameter than w = 2. All data points sit within the Confidence Interval - there is no statistical justification to admit a second mechanism. The wind speeds for 25 and 500-year RP were found to be respectively equal to 43.8m/s and 49.8m/s, which is in reasonable agreement with the wind speeds from the current AS/NZS1170.2 and slightly below those from the recent draft revision of AS/NZ 1170.2. Apart from the possible differences in methodologies, differences may be explained by the use of gust or mean speed, use of enveloped weather stations or roughness analysis. However, the characteristic product (π =7.11) is found to be lower than in the current version of the Standard and very close to the characteristic product of the draft revision.

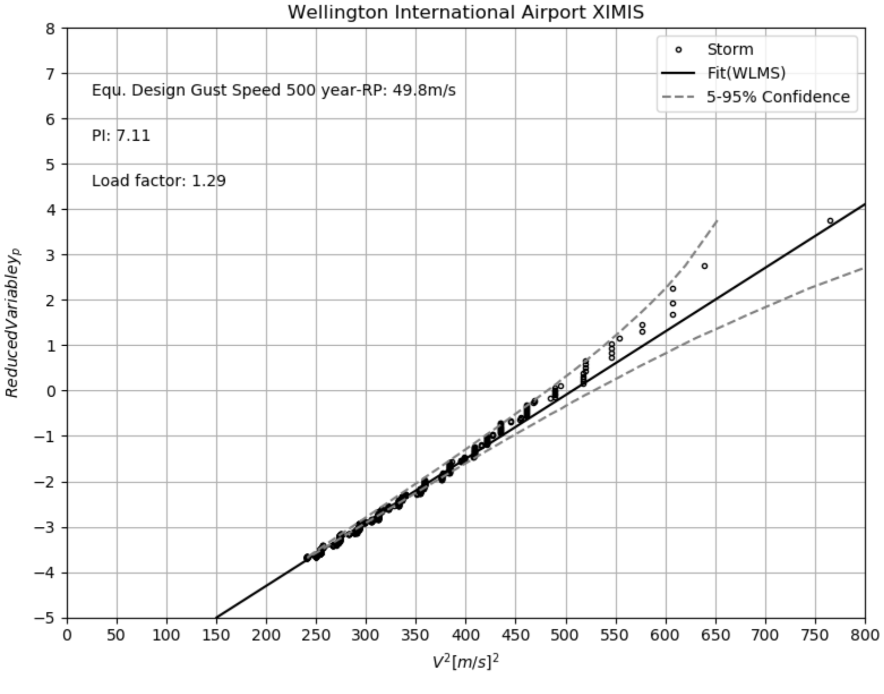

Figure 1: XIMIS V^2-fit to Wellington Airport Data

3.5 XIMIS V^w-Fit

As highlighted in the previous section, the fit was performed on the square of the wind speeds. This was a pragmatic choice to improve the FT1 fit from that directly using the wind speed. Using MS Excel Solver, a 3-parameter fit was performed to explore a possible better choice for the transform $Z = V^w$. A better fit was obtained for a shape parameter equal to 2.55. The same process as before was applied but based on the transformation $Z = V^{2.55}$ with the new fit shown in Figure 2.

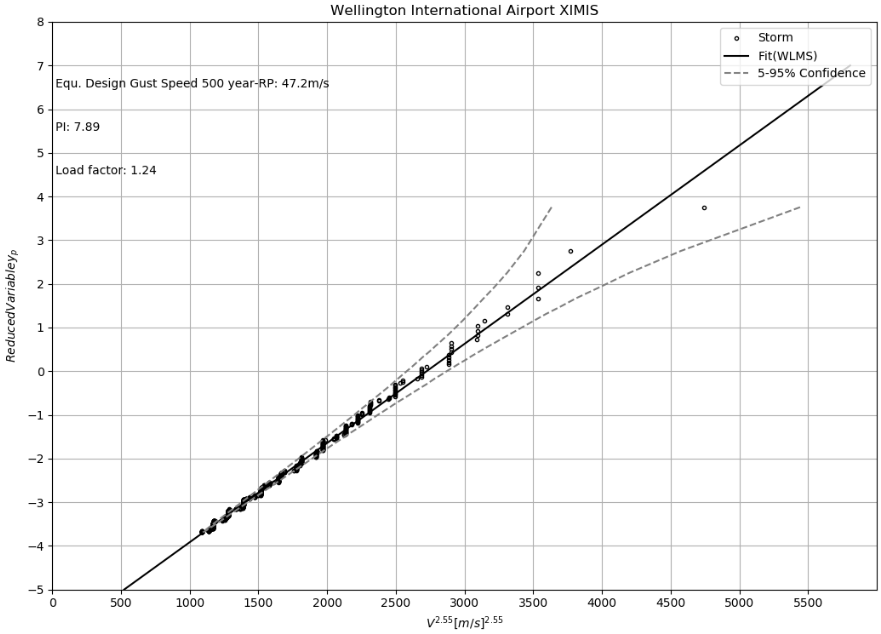

Figure 2: XIMIS $V^{2.55}$-fit to Wellington Airport Data

The $V^{2.55}$-fit shown in Figure 2 is shown to be a better fit than shown in Figure 1 for the V^2-fit. The fitted distribution is now more 'centered' over the observations, i.e. the upward concave curvature observed in Figure 1 seems no longer present. The Weighted Mean Square Error is now found equal to $2.45.10^{-6}$, which is a 10% improvement from the V^2-fit. The equivalent V^2 characteristic product is now even higher than for the V^2-fit, which has the effect to reduce slightly the design wind speed for higher Return Periods. The process above is repeated for the gust speed time-history over the last 7 years only and retaining gust speeds over 45 knots, i.e. over 450 data points contributing to the fit. The shape parameter w is found equal to 2.81, slightly higher than for the mean speeds. The results for the Frontlead weather station are in very good agreement with the results obtained from the Wellington Airport location.

3.7 Summary

To summarize the results above without comparing wind speeds themselves, it is useful to express the results in terms of a load factor. This factor would be the factor applied to the characteristic wind loads (25-year RP) at SLS to calculate the ULS wind loads. The plot of the load factor is shown in Figure 3 below.

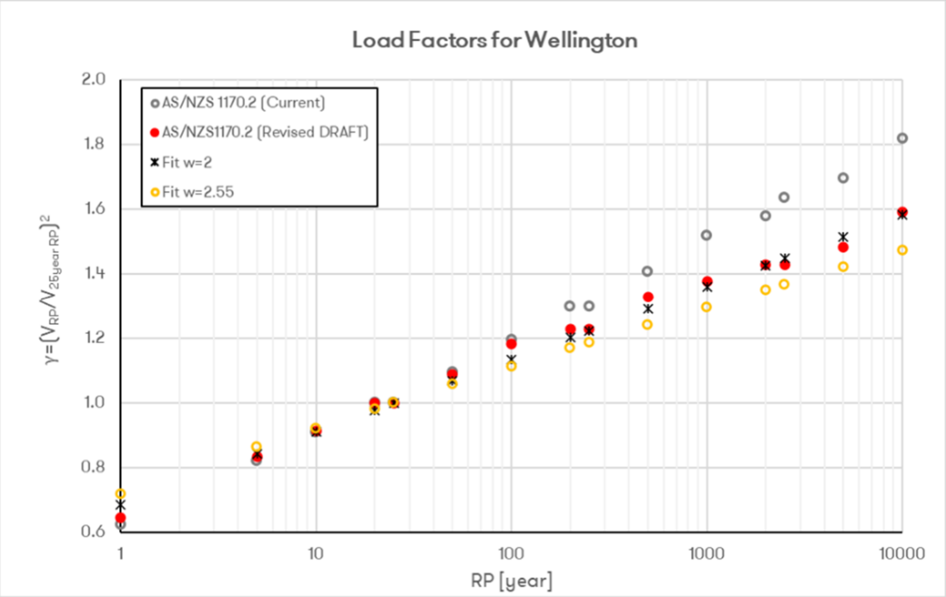

Figure 3 : Comparison Load Factor Standard V. Fit for Wellington Airport

The load factors for recent draft revision of AS/NZ 1170.2 and the XIMIS V^2-fit are in reasonable agreement for all Return Periods and are significantly lower than for the current Standard. However, the improvement from the V^2-fit by implementing a $V^{2.55}$-fit is not negligeable and the load factors are shown to be consistently 4 - 8% lower, hence highlighting the importance of considering inaccuracies associated with the convergence assumption.

3.8 Wind Mechanisms in Wellington

While the data points in all the XIMIS plots for the weather stations considered were shown to remain within the confidence interval, suggesting a simple single mechanism, the Weibull distribution for the northerly winds was found to be irregular which could suggest a mixed climate. An attempt to verify and identify different mechanisms - if any - is made below. The relatively recent methodology by Harris and Cook (2014) using the Offset Elliptical Normal (OEN) model was applied to Wellington. The OEN mixture model for a mixed climate of n disjoints wind mechanism is given as follows:

$$p(x,y) = \sum_{i=1}^{n} f_i \times p_i(x,y) \tag{3}$$

Each distribution p_i can be represented in the x-y cartesian plan by an ellipse rotated and offset from the origin by the mean wind vector. Cook (2019) provided a comprehensive procedure to iteratively fit ellipses to the observed empirical distribution empirical distributions. The results below summarise an initial attempt by the author to use the procedure and differs slightly from the procedure outlined by Cook. The results for the Spring season are shown in Figure 4. The color plot and the contours shown with thin black lines are for the empirical distribution obtained from the observed data and lightly smoothed. The ellipses shown in white are the results of the procedure highlighted above. The frequencies associated with each ellipse are marked in white. Five ellipses were required to obtain a R^2 equal to 0.992. The ellipses are shown to be reasonably well positioned and centered over the various peaks of the empirical distribution. In both cases, strong winds may be identified as a different mechanism from the lighter winds, also potentially slightly shifted in direction. While one mechanism may well dominate the distributions of extremes, it would be valuable to review further the impact of the different components on the Extreme Value Method used earlier.

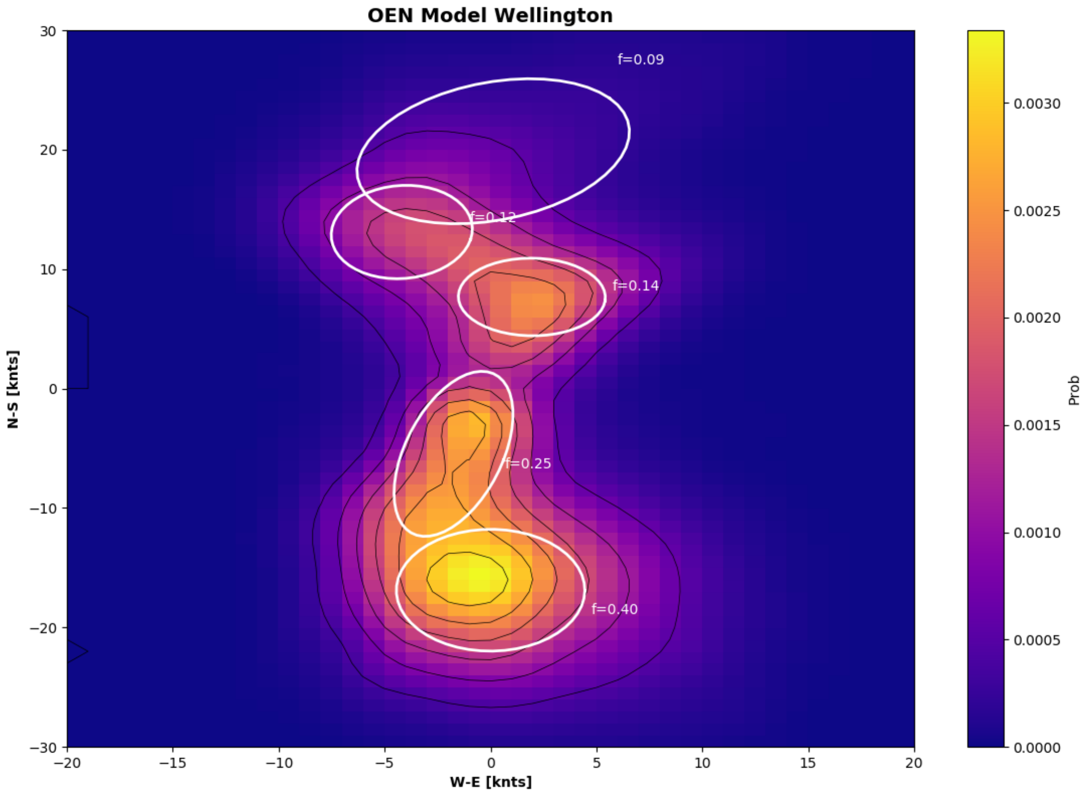

Figure 4: OEN Model for Wellington

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