ESTIMATING LINE-LIKE RISK FOR TROPICAL CYCLONES PART II - ANALYTICAL APPROACH

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Introduction

The approach described in the preceding paper for estimating line-like risk (e.g. for transmission lines) arising from tropical cyclones can be computationally demanding. A more general approach to evaluating the increased risk associated with line-like structures is possible if attention is restricted formally to the gradient balance windfield in the cyclone, although it can be shown that the results apply without any significant loss in accuracy to the windfield at other heights.

The gradient balance equation governing cyclone winds at the 700 mbar height defines the mean (gradient balance) wind speed, V_{GB}, as:

$$V_{GB}(r,\alpha) = \frac{1}{2}(V_T . \sin\alpha - fr) + \{\{\frac{1}{4}(V_T . \sin\alpha - fr)^2 + B . \frac{\Delta p}{\rho} . (\frac{RMAX}{r})^B . \exp[-(\frac{RMAX}{r})^B]\}\}^{\frac{1}{2}}$$

where r = radial distance from the storm centre, α = angle, clockwise positive from storm direction, V_T = storm translation speed, Δp = central pressure difference, RMAX = Radius of Maximum Winds, f = Coriolis parameter, ρ = air density and B = Holland pressure profile exponent parameter.

The above equation can be solved explicitly for any given group of storm parameters (Δp, RMAX, V_T). Hence the maximum value of V_{GB}, denoted henceforth as VMAX, can be determined if the value of DMIN, the closest distance that the storm approaches a particular site, is known. By defining a variable, D, corresponding to distance perpendicular to the storm motion, it is possible to compute the variation of VMAX(D), as shown in Figure 1.

Using the simulation procedure, a set of tropical cyclones can be generated with storm parameters ($\{\Delta p_i, RMAX_i, V_{T,i}\}; i=1,N$). At any fixed value of D, a set of wind maxima can then be computed, ($\{VMAX_i(D)\}; i=1,N$) and fitted by a frequency distribution, conditional upon D, whose resulting cumulative distribution function is written as $F^P_{VMAX/D}(VMAX,D)$. When this is done for a complete range of possible D values, the result is a set of contours of equal CDF magnitude, also shown in Figure 1. These are redrawn to indicate the variation with D of the exceedance probability of some particular value of wind speed, V_0, given by $F^P_{VMAX/D}(V_0, D)$.

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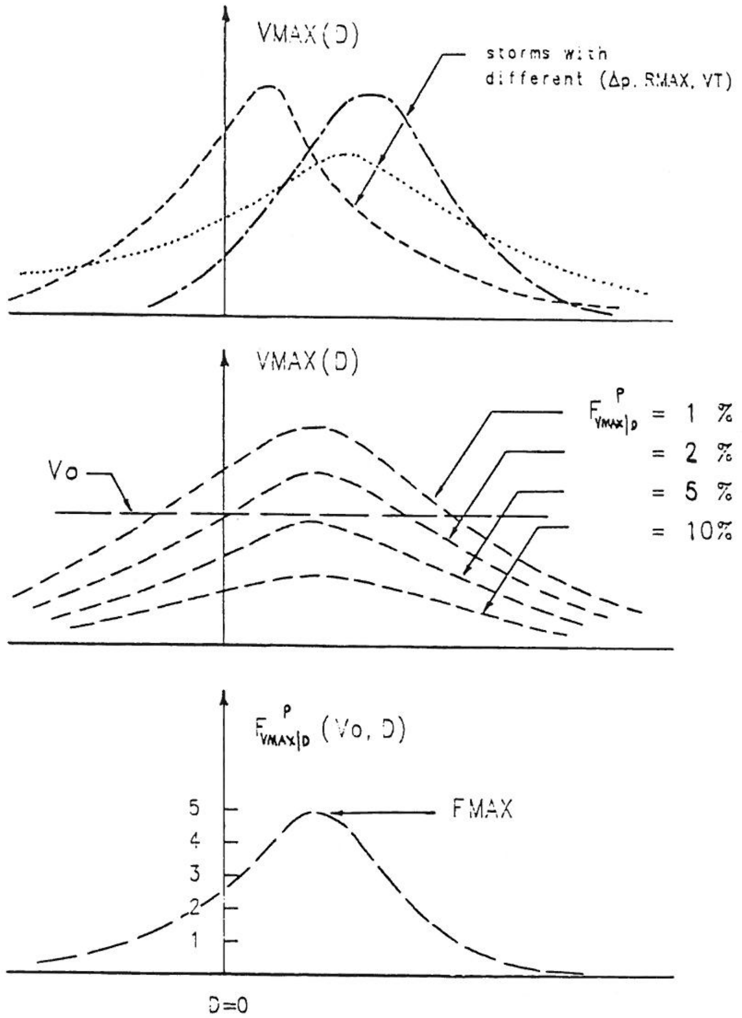

Figure 1 Development of the $F^{P}_{VMAX/D}(V_0, D)$ Curves

From the historical records, it is possible to compute the number density of storm occurrence, $n_D(D)$, equal to the number of tropical cyclones per annum and unit distance crossing the D axis. The exceedance rate for the velocity level, V_0, is then given by:

$$N(>V_0) = \int_{-\infty}^{\infty} n_D(D) \cdot F^{p}_{VMAX|D} \cdot (V_0, D) \cdot dD$$

An examination of historical cyclone records shows that for many coastal locations the variation of the minimum approach distance, DMIN, can be reasonably approximated by a uniform distribution. Therefore, we can now write:

$$N(>V_0) = \overline{n_D} \cdot \int_{-\infty}^{\infty} F^{p}_{VMAX|D} \cdot (V_0, D) \cdot dD$$

For high values of V_0, the exceedances can be assumed to be Poisson distributed and hence the extreme-value distribution of wind speed can be obtained as:

$$F(<V_0) = \exp^{-N(V_0)}$$

The advantage of this particular approach stems from the economy in the number of storms required to establish the extreme-value distribution. This is due firstly to the reduction in computations resulting from the direct integration of the distance to track influence. Secondly, the information required to form the CDF exceedance functions is obtained from storms whose maximum wind speeds exceed the V_0 value. Weaker storms generated in the simulation are not needed in the computations. Hence it is possible to specify a lower cut-off level for Δp values, further decreasing the necessary computations.

Disadvantages arise from the necessity of having to be able to analytically determine the maximum wind speeds for a given value of DMIN, once Δp, RMAX and V_T etc. are known. This is possible for the gradient balance windfield, but not for the 500 metre height and surface windfields although the approximately constant ratios between surface winds and upper-level winds minimises the errors. A more significant problem arises from having to take into account the effects of filling, and the resulting decrease in maximum wind speeds, for locations inland from the coast.

Extension to the Line-Like Risk Problem

This approach can however be used to determine the relative change in risk for line-like structures not affected by the previous constraints. The gradient balance windfield is considered again. This time, a length of line, D_L, spans the storm centre and the resulting VMAX(D) computed. In this case VMAX(D) is the maximum value occurring anywhere along the length of the line.

It can be easily shown that the resulting curve of VMAX(D) is simply an extension of the isolated point curve in Figure 1 with a constant maximum level over a length equal to D_L. The exceedance curves, applying to the line, $F^l_{VMAX/D}$(VMAX,D), shown in Figure 2, are also simple extensions of their isolated point counterparts. The influence of the line is to increase the area in the above integrals, so that the line exceedance rate for a velocity V_0 becomes:

$$N^l(>V_0) = N^p(>V_0) + \overline{n_D} \, . \, FMAX \, . \, D_L$$

where FMAX is the maximum value of $F^p_{VMAX/D}(V_0, D)$. Thus the ratio, $\lambda(V_0)$, of exceedance rate of velocity V_0 for line of length D_L to that of a single point is:

$$\lambda(V_0) = \frac{N^l(>V_0)}{N^p(>V_0)} = 1 + \frac{FMAX \, . \, D_L}{\int_{-\infty}^{\infty} F^P_{VMAX,D}(V_0, D) \, . \, dD}$$

This can be written more conveniently by defining an "effective hurricane line length", D_{eff}, such that:

$$\int_{-\infty}^{\infty} F^P_{VMAX,D}(V_0, D) \, . \, dD = FMAX \, . \, D_{eff}(V_0)$$

The value of D_{eff} depends upon the wind speed, V_0. The exceedance rate ratio for line-like to point structures and the resulting line-like extreme-value distribution can be simply written as:

$$\lambda (V_0) = 1 + \frac{D_L}{D_{eff}}$$

and ...

$$F^l (< V_0) = \exp^{-\lambda (V_0) \,.\, N^p (V_0)}$$

This simple formulation needs to be corrected for two factors. In the above derivation it was assumed that all storms move along parallel tracks (i.e. with the same approach angle) and that the direction of these tracks is perpendicular to the direction of the line. The second factor is simply handled by taking the distance component of the line that is perpendicular to the direction of the tracks. This modifies the above equations so that:

$$\lambda (V_0) = 1 + \sin (\Theta_L) \,.\, \frac{D_L}{D_{eff}}$$

In practice the track angle is not constant, but distributed about some mean direction Θ_0, typically in a Gaussian fashion. The effect of the variation in approach angle is that, when the mean storm approach angle is normal to the line, there will still be a considerable percentage of paths with values of Θ_L less than 90°, decreasing the value of $\lambda(V_0)$. Conversely, lines which run parallel to the mean approach angle will not experience zero increase in risk, as many paths will exhibit values of Θ_L greater than zero.

We can express this by a factor, Φ_L, which depends on the magnitude of the standard deviation of the approach angle, RMS(Θ), about the mean storm direction. Locations on the upper U.S. Atlantic Coast, for example, exhibit "tight" approach angle distributions, RMS(Θ) less than 20°, whereas RMS(Θ) values are typically around 40° for much of the Gulf Coast and over 50° in the Florida Peninsula region. A reasonable value for the Φ_L factor has been estimated as RMS(Θ)/500.0. This last correction gives the ratio of line-like to point exceedance rate as:

$$\lambda (V_0) = 1 + \{\{ 3 \Phi_L + (1 - 4 \Phi_L) \,.\, \sin (\Theta_L) \}\} \,.\, \frac{D_L}{D_{eff}}$$

The advantage of this approach is that only the computations for a single point need to be used. These have been previously carried out for the Galveston area. The values of D_{eff} vary considerably over the range of velocities of interest. D_{eff} equals 88 km at the 100-year return speed estimate of 48.0 m/sec. In the Galveston area, the rms value of approach angle is 42.8°. Hence the value of Φ_L is 0.086.

If two lines of length 100 km are considered, one running parallel to the coast and the other inland, which coincide approximately with values of Θ_L equal to 90° and 0° respectively, then the increase in exceedance rates for wind speeds in the range 45–50 m/sec are approximately 1.7–2.0 and 1.1–1.2 respectively. These figures translate into reductions of the corresponding return period of 50–60% and 10–20% respectively, which agree very well with the actual figures calculated in the previous paper using the simulation approach.