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Tornado risk model for transmission line design

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Abstract

A tornado risk model is developed for transmission line design. This model is based on an extension to the McDonald, (NUREG/CR-3058,1983) model for point structures, and has been developed such that it can be simplified for applications in codes of practice and design recommendations. Tornado statistics obtained for South Africa are presented to illustrate the application of the model.

Keywords: Tornado; Risk model; Transmission line

1. Introduction

The design of transmission line structures is typically governed by wind loading, and in some parts of the world, wind loading in combination with ice loading. The wind load used in most codes of practice and design recommendations for transmission line design [2–5] have until recently been based almost exclusively on large-scale wind storms, which may include severe storms such as hurricanes and typhoons. Very limited guidance is given in codes of practice on severe local wind storms such as tornadoes and downbursts – despite the fact that the vast majority of transmission line failures due to wind loading have, in fact, been due to extreme winds arising from severe local wind-storm events. To date, the only code of practice or design recommendation for transmission line structures that makes specific reference to tornadoes is the recent ASCE draft guidelines [6].

There are various tornado risk models available in the literature, which historically have shown a natural progression from the simplified model developed by Thom [7] which does not depend on wind speed, to the Wen and Chu model [8] and Garson et al. [9] that introduced the variation of wind speed across the width of the tornado, through to the Twisdale and Dunn [10] and the McDonald [1] models

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which take into account both the variation in wind speed across the width of the tornado as well as the variation in damage along the length of the tornado. Most of these models have been developed for "point structures", in which the lateral dimensions of the structure are small or of the same order as a width of the tornado. Transmission lines, on the other hand, traverse large distances, with dimensions that are several orders of magnitude greater than the width of a tornado. The probability of a tornado striking a transmission line anywhere along the length of the transmission line is therefore significantly larger than that of a strike at an isolated point.

The risk of a tornado striking a "line structure", such as a transmission line, has been investigated by Twisdale and Dunn [10] and more recently de Schwarzkopf and Rosso [11]. These models have been based on Monte Carlo simulation techniques, and therefore cannot be easily generalised for use in codes of practice. In the present paper, a tornado risk model is developed such that it can be simplified for applications in codes of practice and design recommendations.

2. Tornado activity in South Africa

Tornado activity in South Africa is first briefly reviewed in order to present the necessary statistics required for the transmission line risk model. Full details of tornado activity in South Africa are given in Ref. [12].

An analysis of tornado activity in South Africa was based primarily on a list of extreme weather events published in selected Weather Bureau Newsletters covering the period 1905–1987 [13], together with a more recent Weather Bureau Publication [14]. As far as possible this data was verified by extracting the original newspaper articles, obtained largely from the archives of the State Library. In addition, a comprehensive survey of the local literature, Weather Bureau Newsletters [1953–1991] and newspaper clippings collected since 1913 by the Weather Bureau Library was also undertaken, which resulted in the identification of several additional tornadoes. Further information was also obtained from CSIR research reports documenting some of the larger tornado events. At present the database of tornado activity contains descriptions of over 180 tornadoes.

The mean rate of occurrence of tornadoes per unit area per year was evaluated by Milford and Goliger [12] using a Kriging analysis [15], introducing a 25 km by 25 km grid. A window size (or filter) of 90 km was used to provide statistically stable results. The resulting mean rate of occurrence of tornadoes per year per square kilometer for South Africa is shown in Fig. 1. Note that tornadoes of intensity F0 have been excluded from the analysis presented in Fig. 1, as many of these events have gone unreported and the database was incomplete for these events. Three tornado zones are defined in Fig. 1, namely, zones A, B and C, where zone A corresponds to the highest tornado risk level.

The probability distribution of tornado intensity (excluding F0) is shown in Fig. 2. For later use, a probability distribution of tornado intensity for the USA (based on 1971–1975 tornadoes) is also included in Fig. 2, obtained from Abbey [16] (including tornadoes of intensity F0).

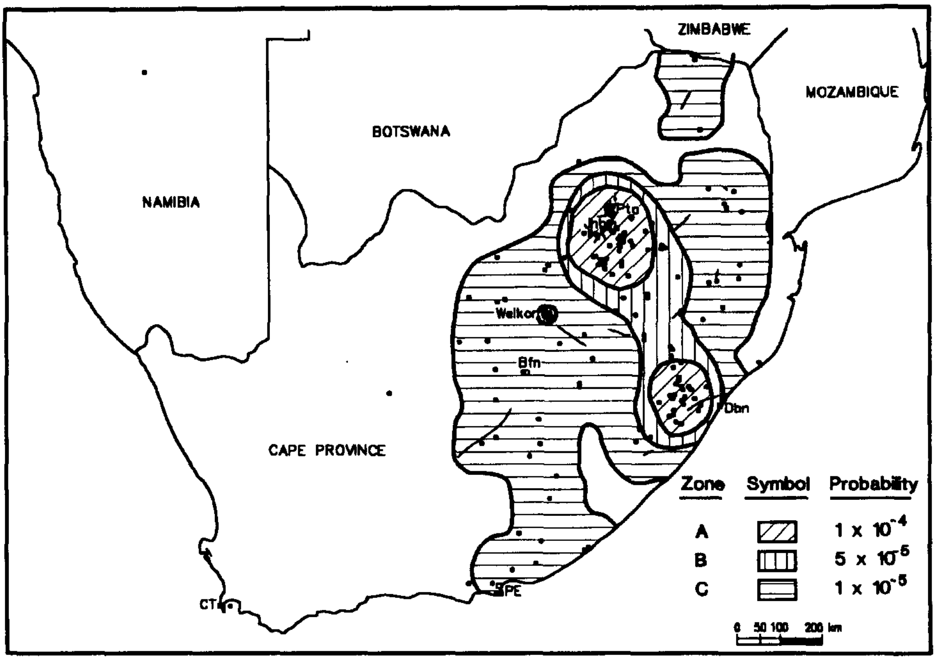

Fig. 1. Mean rate of occurrance of tornadoes (excluding tornadoes of intensity F0).

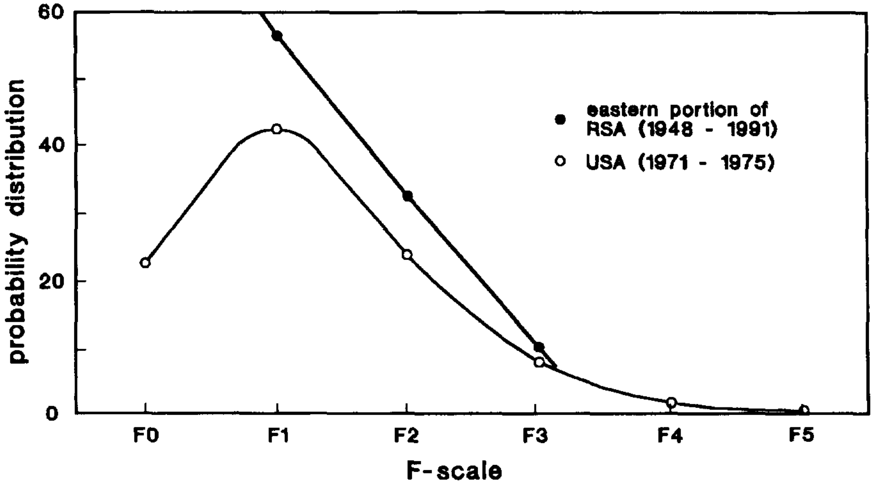

Fig. 2. Probability distribution of tornado intensity (South Africa: excluding tornadoes of intensity F0; USA: after Abbey, 1976).

Limited information regarding the path width and path length of tornadoes is available for South Africa. A comparison of the Fujita/Pearson [17] path length descriptors with the lengths of the South African tornadoes is presented in Fig. 3. Although a significant scatter is present, a satisfactory correlation can be seen. Further, as there is no information available in South Africa from which the variation in wind speed along the length of the damage path could be assessed, it has been assumed that the path length factors given in Table 1 and obtained from an analysis of the measured damage paths resulting from the Super Outbreak of Tornadoes of 3–4 April 1974 in the USA (after Ref. [10]) are applicable to South African conditions. This approach has also been adopted in Argentina [11], and any errors introduced by this assumption are likely to be small for tornadoes of intensity F3 or less. (To a certain extent, the above assumption can also be supported by the research of d'Abreton [18] who showed that both South African and North American tornadoes are formed under similar synoptic and thermodynamic conditions.)

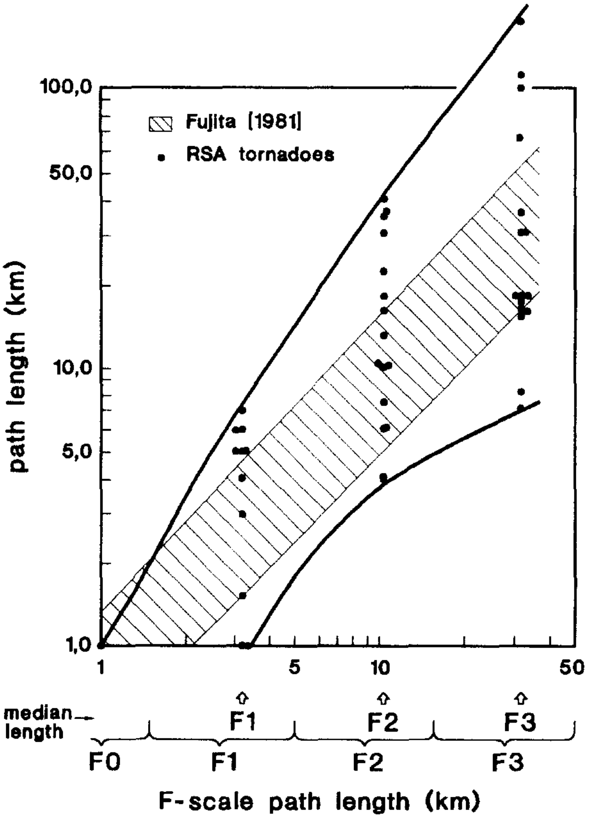

Fig. 3. Comparison between measured path lengths and Fujita classification system.

3. Tornado risk model for transmission line design

A tornado risk model for transmission lines, based on the McDonald [1] approach, is developed in this section. Consider the probability of a tornado of intensity F_i striking a short section of a transmission line of length L_k (km). Let l_i denote the path length of the tornado, and assume that:

- the mean rate of occurrence of tornadoes is constant along the section of the transmission line L_k;
- for the present, assume that the wind speed is constant along the damage path;
- the probability of a tornado strike on one section of the line is independent of a strike on another section;
- all tornadoes are perpendicular to the transmission line.

It follows that the average number of tornadoes of intensity F_i per year striking the section of transmission line of length L_k (or the probability of a strike, $P_{sk}\,(F = F_i)$ within an area A can then be expressed as:

$$\begin{aligned} P_{sk}(F = F_i) &= \frac{n_i}{A} l_i L_k \\ &= \frac{N}{A}\frac{n_i}{N} l_i L_k \\ &= L_k \mu P(F = F_i) l_i, \end{aligned}$$

where n_i is the number of tornadoes per year of intensity F_i within the region A (km^2), μ the mean occurrence rate of tornadoes (number/km^2/year), N the total number of tornadoes per year within the region, and $P(P = F_i)$ is the probability distribution function of tornado intensity.

Now let $\alpha_{ij}.l_j$ denote the length within the damage path that experiences wind speeds within the F-scale interval v_i in a tornado F_j whose maximum wind speed is in the interval v_j, $(j \geqslant i)$ (km) (see Table 1). Considering all tornadoes, the probability that a section of the transmission line of length L_k will experience a wind speed that is contained in the F-scale interval v_i is given by the expression

$$P_{sk}(v = v_i) = L_k \mu \sum_{j=1}^{5} \alpha_{ij} l_j P(F = F_j).$$

It follows that the probability that a wind speed greater than or equal to v_i will be experienced along the length L_k is then obtained as

$$\begin{aligned} P_{sk}(v \geqslant v_i) &= \sum_{j=i}^{5} P_{sk}(v = v_j) \\ &= L_k \mu R_l(v_i), \end{aligned}$$

where $R_l(v_j)$ is a *tornado damage length function*, obtained as

$$R_l(v_i) = \sum_{j=i}^{5} \sum_{k=j}^{5} \alpha_{jk} l_k P(F = F_k).$$

Table 1
Path length adjustment factors, a_{ij} (after Twisdale and Dunn, 1983) [10]

Local path length intensity, I_i	Maximum tornado intensity, F_j					
	F0	F1	F2	F3	F4	F5
v_j = F0	1.000	0.572	0.280	0.116	0.142	0.133
v_j = F1	0.000	0.428	0.352	0.245	0.158	0.102
v_j = F2	0.000	0.000	0.368	0.318	0.278	0.189
v_j = F3	0.000	0.000	0.000	0.321	0.210	0.242
v_j = F4	0.000	0.000	0.000	0.000	0.212	0.185
v_j = F5	0.000	0.000	0.000	0.000	0.000	0.149

The tornado damage length function is given in Fig. 4 for both South Africa and the USA, obtained using the probability distributions of tornado intensity given in Fig. 2. It can be seen that both lines exhibit similar trend with the risk function for the USA being higher due to the contribution of large tornadoes (F4 and F5) which have never occurred in South Africa.

The analysis presented so far has only considered a short length of transmission line, and it has further been assumed that the mean rate of occurrence of tornadoes is constant along the section of the transmission line. Assuming that tornado events constitute a Poisson process the probability that a wind speed v_i will be exceeded anywhere along the length of the line can now be obtained for small probabilities as

$$P_{sL}(v \geqslant v_i) = 1 - \prod_k [1 - P_{sk}(v \geqslant v_i)]$$

$$\approx \sum_k P_{sk}(v \geqslant v_i).$$

Assuming a unit length of transmission line, L_k (km) it follows that

$$P_{sL}(v \geqslant v_i) \approx L \sum_k \mu_k R_I(v_i),$$

where L is the total length of the transmission line (km), and μ_k is the mean annual rate of tornadoes (number/km^2/year) within region k.

Of interest to note is that Twisdale and Dunn [10] have also investigated the effect of the size of the structure on the wind speed probabilities, including transmission lines, using Monte Carlo simulation. From the analysis for transmission lines, Twisdale and Dunn suggested that an approximate manner to account for the length of the structure is to increase the "point probability" of tornado wind speed exceedence by 10 times the number of miles of the length of the structure. This suggestion, however, appears to be incomplete, as it can be shown that Twisdale and Dunn's results, in fact, reflect that the probability of a threshold wind speed being

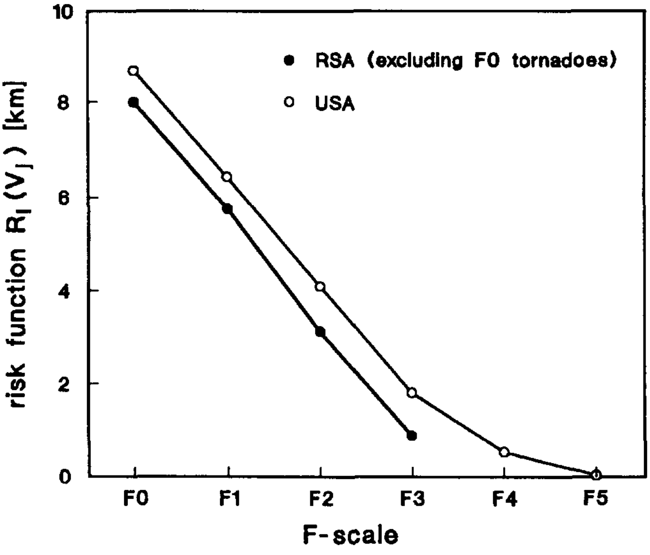

Fig. 4. Tornado damage length function.

exceeded on a transmission line of length L (in miles) can be expressed as

$$P_L(v \geqslant v_i) = 1 - [1 - P_k(v \geqslant v_i)]^L$$
$$\approx LP_{sk}(v \geqslant v_i).$$

Note that in the model for transmission lines derived here, the variation in the wind speed across the width of the tornado has been neglected. This model, therefore, represents the probability that the maximum wind speed will be exceeded anywhere along the transmission line. (The actual wind loading acting on the transmission line will, however, vary according to the tornado model adopted.)

It should also be noted that this model is conservative in that the effect of tornado path direction has been neglected. It should further be noted that additional complications come into play when this model is applied to isolated points along the line structure, such as transmission towers. Ideally, a point risk model should be used in this case, taking into account the variation in the wind speed across the tornado width, as well as using the width of the tower when determining the damage path. The joint probability between the wind loads acting on the tower and on the transmission lines should then also be considered.

4. Applications

Structures are not only subject to tornadic winds, but also to thunderstorms and large-scale wind storms. For small probabilities, the probability of a threshold of a threshold wind speed being exceeded due to all these effects can be approximated by

$$P(v \geqslant v_0) \approx P_0(v \geqslant v_0) + P_t(v \geqslant v_0),$$

where $P(v \geqslant v_0)$ is the probability of a wind speed v_0 being exceeded due to thunderstorms and large-scale storms; and $P_t(v \geqslant v_0)$ is the probability of a tornadic wind speed v_0 being exceeded.

Based on the results obtained by Milford [19], the annual maximum probability distribution $P_0(v \geqslant v_0)$ for the 3 s gust speed can be approximated for most of South Africa by the following expression:

$$P_0(v \geqslant v_0) = 1 - \exp[-\exp[-8.47[(v_0/40)^2 - 0.538]]].$$

Note that the use of the 3 s gust speed is an approximation only, but is satisfactory for the present purposes.

The resulting combined probability distribution is given in Fig. 5 for zones A, B and C obtained from Fig. 1 for South African conditions, and for transmission lines of 1, 10 and 100 km in length. From Fig. 5 it can be seen that for low wind speeds the wind climate is determined by conventional thunderstorm winds and large-scale storms. However, for high wind speeds the climate is dominated by tornadoes, in particular, for long transmission lines.

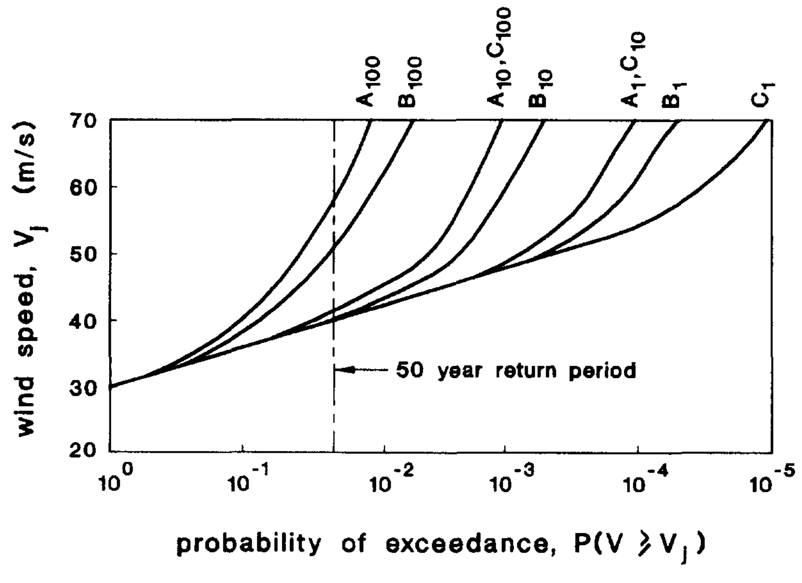

Fig. 5. Annual probability of exceeding threshold windspeed.

5. Summary and conclusions

A tornado risk model for transmission line design has been developed. The risk model is based on the McDonald [1] model, but is expanded in terms of damage length of the tornado and the length of transmission line (as opposed to the damage area of the tornado which is applicable to point-like structures). The model does not take into account the orientation of transmission line relative to the tornado path, or the point-wise nature of the individual transmission line towers.

Relevant statistics from South Africa are presented to illustrate the application of the model together with tornado risk areas for South Africa. Of interest to note is that in the highest risk areas in South Africa the occurrence of tornadoes per square kilometer is comparable with the lower risk regions in the mid-western USA.

Acknowledgements

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