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A Probabilistic Tornado Wind Hazard Model for the Continental United States

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ABSTRACT

A probabilistic tornado wind hazard model for the continental United States (CONUS) is described. The model incorporates both aleatory (random) and epistemic uncertainties associated with quantifying the tornado wind hazard parameters. The temporal occurrences of tornadoes within the continental United States (CONUS) is assumed to be a Poisson process. A spatial distribution of tornado touchdown locations is developed empirically based on the observed historical events within the CONUS. The hazard model is an aerial probability model that takes into consideration the size and orientation of the facility, the length and width of the tornado damage area (idealized as a rectangle and dependent on the tornado intensity scale), wind speed variation within the damage area, tornado intensity classification errors (i.e.,errors in assigning a Fujita intensity scale based on surveyed damage), and the tornado path direction. Epistemic uncertainties in describing the distributions of the aleatory variables are accounted for by using more than one distribution model to describe aleatory variations. The epistemic uncertainties are based on inputs from a panel of experts. A computer program, TORNADO, has been developed incorporating this model; features of this program are also presented.

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KEYWORDS: tornado hazard; probabilistic hazard model; epistemic and aleatory uncertainties; Fujita scale; tornado intensity; intensity classification error.

1. INTRODUCTION

For designing critical and hazardous facilities, the tornado wind hazard at a facility is generally described in terms of a probabilistic hazard curve. This curve quantifies the hazard in terms of the expected frequency, per year, that tornado wind speeds at a facility exceed a given velocity, over a range of velocities. The hazard curve is used to estimate the expected frequency or occurrence interval for a specific wind speed or, conversely, to assess a design-basis wind speed for a specified hazard level. Two types of tornado wind hazard models are commonly used: point-strike models or aerial models. A point-strike model treats the target as a point (unit area), so the hazard is described at a point or unit area. Examples of point-strike models are the Thom (1963), Abbey and Fujita (1975, 1979), Ramsdell (Ramsdell, et. al., 1986) and McDonald (1980, 1996) models. Unlike a point-strike model, an aerial model considers the dimensions and orientation of the facility in determining the wind hazard at a facility. Hazard assessments using aerial models can be based on assessing the probability that a specified wind speed occurs somewhere within the facility area (union definition of a tornado strike) or the entire facility experiences a specified wind speed (intersection definition of a tornado strike). Examples of aerial models are the Twisdale (1978) and Reinhold and Ellingwood (1982) models. Almost all of these models assume that tornado touchdowns occur uniformly throughout a relevant area surrounding the facility.

The model described in this paper is an aerial model that considers tornado touchdowns occurring non-uniformly throughout the CONUS. The model is designed for site-specific risk assessments at sites anywhere in the CONUS. It is based on probabilistic risk assessment methodologies, which have been used to estimate the risks and/or hazards of other natural hazards, e.g., earthquakes, hurricanes, floods, as well as technological risks, e.g., aircraft crashes, production and other operational accidents. The existence of a credible database of the touchdown locations of historical tornadoes throughout the CONUS is essential. The United States Storm Prediction Center (SPC) database is used in the computer program TORNADO, developed to implement the model. Also crucial to the model is the availability of estimates of the following model 'parameters':

- Expected number of tornadoes per year, i.e. tornado occurrence rate.
- Distribution of F-scale intensity (Developed by Theodore Fujita of the University of Chicago, F-scale is the most widely used method of classifying a tornado based on observed/surveyed damage. Each F-scale intensity has been assigned a wind speed range).
- Misclassification matrix (that probabilistically quantifies the errors in each of the seven F-scale intensities).
- F-scale to wind speed relation (Since the damage assessment for intensity classification is subjective, wind-speed assigned to a F-scale has uncertainties associated with it).
- Distribution of the tornado heading, i.e. direction (This would account for any directional bias that tornadoes may have).
- Distribution of the tornado damage area length and width (This would account for the variation in the length and width of the area damaged by tornadoes of different intensities).
- Variation in wind speeds within the damage area.

These parameters are used to describe the aleatory (random) variability of tornado occurrences and characteristics. The model recognizes that the available information regarding these parameters is based on observations and analyses of the historic tornadoes, hence represents only an estimate of reality. Further, in order to account for the fact that some of the tornado characteristics (e.g., occurrence rates or F-scale intensity distributions) are not uniform throughout the CONUS, the model recognizes epistemic, (modeling) uncertainty as well. This is included by allowing for alternatives 'values' of the model parameters and a measure of relative confidence in the adequacy/goodness/reality of each of the alternatives.

2. TORNADO WIND HAZARD MODEL

The tornado wind hazard model is based on treating tornado occurrences and the characteristics of tornadoes as aleatory variables. The temporal occurrence of tornadoes throughout the CONUS is assumed to be a stationary Poisson process. Given a site of interest, and letting λ denote the occurrence rate (per year) of tornadoes in an appropriate area surrounding the site, the expected frequency (per year) of wind speeds exceeding v mph at the site, i.e., the tornado wind hazard at the site, is

$$EF(V>v) = \lambda \; P(V>v|\text{a tornado})$$

The conditional probability, given a tornado touches down, that the wind speeds at the site exceeds v, $P(V>v|\text{a tornado})$, depends on the intensity of the tornado. The model uses the standard F-scale intensity classification, F0 through F5, of tornadoes. Given the F-scale intensity distribution, $P(Fj)$, $j=0,1,..\ 5$, the tornado wind hazard at the site is

$$EF(V>v) = \lambda \sum_i \; P(V>v|\ Fi)\ P(Fj)$$

The model allows for the potential misclassification of tornado intensities due to random encounter of structures and human errors in classification. These sources of variability/uncertainty are treated as a random (aleatory) uncertainty based on the following rationale: Given a tornado, there is a maximum wind speed associated with it, generally unknown. This wind speed has the capability of producing a given amount of damage (e.g., F3 intensity damage) provided the opportunities to produce damage exist. The existence of opportunities is a function of the touchdown location, the tornado path, and the number and locations of structures, trees, vehicles, etc. within the damage area. These are issues of the state of nature and the world, thus, classification errors due to the existence of opportunities is considered an aleatory variable. Since tornado intensity classification involves human judgement there is also a source of epistemic uncertainty in the intensity classification process. However, it is assumed that the aleatory variability is the dominant source of uncertainty. Let p_{ij} denote the probability that the true intensity is Fi, given that the recorded intensity is Fj. Accounting for classification errors, the tornado wind hazard is

$$EF(V>v) = \lambda \sum_i P(V>v| Fi) (\sum_j p_{ij}P_R(Fj))$$

$$= \lambda \sum_i P(V>v| Fi) P_T(Fi)$$

where, $P_T(Fi) = \sum_j p_{ij} P_R(Fj)$

If it is assumed that touchdown locations are uniformly distributed within a region of interest, the probability that the wind speed exceeds v mph at an arbitrary point in the region, P(V>v|Fi), is proportional to the size of the sub-area of the tornado damage area in which the wind speed exceeds v. An estimate of this probability is A(v|Fi)/A, where A is the area of the region of interest and A(v|Fi) is the average size of the sub-area in which wind speeds exceed v, given an Fi level tornado. Applying the usual quantification of the variability of wind speeds within the damage area in terms of 'local intensities', the estimate of this probability is

$$P(V>v|Fi) = \sum_{j\leq i} P(V>v| Fj, Fi) A(Fj|Fi)/A$$

The term P(V>v| Fj, Fi) recognizes that wind speeds associated with local intensity Fj vary within a range of speeds. The model assumes that the wind speeds are uniformly distributed within the range. Inserting this into Equation (4), the tornado wind hazard is

$$EF(V>v) = \lambda \sum_i (\sum_{j\leq i} P(V>v| Fj, Fi) A(Fj|Fi)/A) P_T(Fi)$$

The revised model extends this model in two ways, (1) the site or facility is treated as an area rather then a point and (2) a non-uniform distribution of tornado touchdown locations within the affective region around the site is used. To estimate the tornado wind hazard when the site is an area, it is necessary to identify the 'tornado origin area' (Twisdale, 1978). Using the union definition of a tornado strike, this area is the set of tornado touchdown locations for which wind speeds at some point at the facility are greater then v mph. To identify the 'tornado origin area', it is necessary to model the tornado damage area. The model approximates the damage area as a rectangular area (Twisdale, 1978). The length and width of the damage area are considered aleatory variables. The joint distribution of length and width depends on the F-scale intensity of the tornado. It is also necessary to consider wind speed variation within the damage area. Areas of increasing 'local intensity' are modeled as included rectangles, centered, lengthwise, at the center of the damage area. Along the width of the damage area the included rectangles are offset from the storm center track to the right in recognition of the existence of suction vortices rotating about the parent tornado (Abbey and Fujita, 1979). The tornado origin area depends on the dimensions and orientation of the facility and the direction of the tornado path, as well as the characteristics of the damage area.

Mathematically, allowing for a non-uniform distribution of tornado touchdown locations and an aerial model, the term A(Fj|Fi)/A changes to the integral of the density function of the distribution of touchdown locations within the tornado origin area corresponding to Fj local intensity. The location and dimensions of this area depend on the tornado F-scale intensity, Fi; the direction of the tornado path,_; the length and width, $(L, W)_i$, of the damage area; and the proportion of the damage area involving winds of local intensity Fj. The lengths and widths of the local intensity areas are expressed as fractions, $(\_{L}, \_{W})_{ij}$, of the damage area lengths and widths respectively. The revised mathematical expression for the wind hazard is

$$EF(V>v) = \_ \_ {}_i P_T(Fi) \{\_ {}_j P(V>v\_ Fj, Fi) \_ {}_{A(Sij)} dF(x, y) \}$$

where, F(x, y) denotes the distribution function of the tornado touchdown locations and Sij denotes the parameters { _, $(L,W)_i$, (_

L, _W)$_{ij}$ } which define the local intensity areas. Since the parameters are aleatory variables, the calculation averages over the probability distributions of these aleatory variables. In the model, distributions are used for the tornado path direction and damage area length and width; singular values, dependent on the local intensity and F-scale intensity, are assumed for the dimensions of the local intensity areas. Adding this to the model, the mathematical expression for the tornado wind hazard is

EF(V>v) = _ _ $_i$ P_T(FI) { _ $_j$ P(V>v_ Fj,Fi) _– _ $_{(L,W)i\ \_A(Sij)}$ dF(x,y) dG(_) dH(L,W)} (8)

This is the basic model in the TORNADO code that has been developed to create the tornado wind hazard curves.

3.0 COMPUTER PROGRAM TORNADO

The tornado wind hazard model described in Section 2 forms the basis for the computer program TORNADO that is used to develop site-specific tornado wind hazard curves. The program assumes that the facilities at the site can be approximated by a set of convex polygons. The inputs into the program are:

1. The location of the site, given by the (latitude, longitude) of the site. This is treated as the center of an (x, y) coordinate system for defining the dimensions of the facility.

2. The (x, y) coordinates of the corners of the convex polygon(s) identifying the facility.

Also required are data on the locations and characteristics of tornadoes, specifically:

a. A database of the historical tornado touchdown locations within the CONUS. Included in the current version of the code is a database of locations based on the Storm Prediction Center's (SPC) database of tornadoes for 1950-1995.

b. Alternative estimates, with epistemic uncertainties, of the model parameters identified in Section 1.

Central to the wind hazard calculations is the development of a probability distribution of the touchdown locations of tornadoes throughout the CONUS. Given the database of touchdown locations of the historical tornadoes, a 2-dimensional normal kernel density estimator is used to estimate the distribution of tornado locations throughout the CONUS

$$(x_1, x_2) = \frac{1}{2\pi n h_1 h_2} \sum_{i=1}^{n} Exp\left[-\frac{1}{2}\sum_{j=1}^{2}\left(\frac{x_j - x_{ij}}{h_j}\right)^2\right]$$

where, (x1,x2) and (x_{i1}, x_{i2}), i= 1,…,n are the (latitude, longitude) of an arbitrary location in the CONUS and the touchdown locations of the historical tornadoes respectively. The smoothing parameters, h_1, h_2, used in the current version of TORNADO are a fraction of $\sigma_i n^{-1/6}$, where, n is the number of tornadoes in the touchdown location database and the $\_{}_i$ are estimates of the standard deviations of the recorded latitudes and longitudes. The smoothing parameters reflect the variability of future tornado locations relative to the locations of the historical events.

Given the sets of values of the model parameters and the site-specific location and facility dimensions, the program identifies a site specific tornado effect area (SSTEA). The SSTEA is defined by the locust of touchdown locations from which a tornado could start and have the potential to affect the facility. It is based on the potential longest tornado path length. Given the SSTEA and the database of historical tornado locations, the program conceptually estimates a site-specific occurrence rate and a conditional location distribution over the SSTEA. This forms the basis for the site-specific hazard calculations.

The output of TORNADO is an estimate of the tornado wind hazard curve for the site. Since the model includes epistemic uncertainty, the estimate is a set of hazard curves representing envelopes of hazard fractiles produced by the epistemic uncertainties.

4.0 TREATMENT OF UNCERTAINTY

Since the true values of the model parameters listed in Section 1 are not known exactly and can only be estimated, a very important aspect of the model is the inclusion of epistemic uncertainties reflecting the current state of knowledge about parameters. This is included in the model by allowing for alternative values of the model parameters along with a measure of the relative confidence that each of the alternatives approximates the true value of the parameter. The credibility of the estimated tornado wind hazard curves depends on the credibility of the values of the model parameters. Thus, it is important that the values be derived with direct interaction and involvement of industry experts in the field. A panel of experts was formed to elicit input about the model parameters. A discussion of the information elicited is included in the following subsections.

4.1 Occurrence Rate of Tornadoes

An obvious source of an estimate for the occurrence rate is a database of historical tornadoes, such as the SPC database. Depending on the years selected, the estimated occurrence rate can vary between approximately 650 and 1200 per year. Estimated rates for several periods were provided to the experts. They were asked to provide their estimate of a lower and upper bound for the rate and their relative confidence that the rate does not exceed several intermediate values. From this input, a 'consensus' uncertainty distribution of the occurrence rate will be developed.

4.2 F-scale Intensity Distribution

Since an F-scale intensity is assigned to all recorded tornadoes, the obvious source of estimates for the probability distribution of the recorded F-scale intensity is the database of historical tornadoes. Since the parameter is a probability distribution instead of a single-valued parameter, the credibility of an estimate depends on the number of years used as well as the time period. Thus, several time periods of varying length were provided to the experts and they were asked to provide their relative confidence in each. The expert's inputs will be combined to develop a 'consensus' weighting of the various time periods, hence, weighting of the estimated recorded F-scale intensity distributions.

4.3 Probabilities Associated with Classification Errors: Misclassification Matrix

The misclassification matrix provides a means of accounting for errors in the F-scale classification of tornadoes. Misclassification is quantified in terms of the conditional probability, p_{ij}, that the true intensity of a tornado is Fi, given that the recorded intensity is Fj. The misclassification matrix is the matrix of the probabilities, p_{ij}, used to assess the distribution of true F-scale intensity, given the distribution of recorded intensity. Based on a review of the tornado literature, most estimates of misclassification matrices include both evaluation and random dispersion uncertainty. The aleatory aspects of these uncertainties are assumed to be the dominant sources of error. Several alternative estimates of the misclassification matrix, based primarily on the work of Twisdale (1978, 1981, 1983) and Reinhold and Ellingwood (1982) were provided to the experts. They were asked to provide their relative confidence in each alternative.

4.4 F-scale Intensity to Wind Speed Relation

Several models for associating wind speeds to each of the F-scale intensities have been developed. One is the original association of wind speeds and damage developed by Fujita (1973). Two other relations in the literature were developed by Twisdale (1978) based on a Bayesian analysis of the range of wind speeds associated with the F-scale intensities. One assumes a uniform uncertainty on the upper bounds of the wind speed intervals related to each F-scale intensity level. The second assumes a linearly increasing uncertainty on the upper bound. Another relation was developed by Dames and Moore (Beebe, et. al, 1975). The experts were asked to provide their relative confidences in each of these alternative relations.

4.5 Distribution of Tornado Path Direction

Elicitation of uncertainties in estimates of the distribution of tornado path direction was done in the same way as that for the distribution of F-scale intensity.

4.6 Distribution of Damage Area Length and Width

The damage area of a tornado is modeled as a rectangle with specified length and width. Aleatory variation in the damage area is represented by a joint probability distribution of length and width, conditional on the F-scale intensity of the tornado. Data from the database of historical tornadoes is the basis for estimating the joint distribution. Epistemic uncertainty was quantified by having the experts provide their relative confidence in using data from several alternative time periods to estimate the joint probability distribution.

4.7 Variation in Wind Speeds Within the Damage Area

Cascading rectangular sub-areas of diminishing size within the damage area are used to model the wind speed variation within the damage area. The lengths and widths of these included sub-areas, specified as fractions of the length and width of the damage area, are functions of the F-scale intensity. The fractions for each of the higher intensities (e.g., F2 and F1 for an F2 intensity tornado) are model parameters. Several alternative sets of values for the length fractions, including those by Fujita(1978), MacDonald(1980), Twisdale(1981), and Reinhold and Ellingwood(1982) were considered. Similarly, several alternative sets of values for the width fractions were developed for inputs. These included fractions based on the Dapple values developed by Abbey and Fujita (Abbey & Fujita, 1979) and on values based on the work of Garson, et. al(1975), Reinhold & Ellingwood,(1982) and McDonald(1983). Combinations of sets of length and width fractions were provided to the experts for their assessment of their relative confidence in each combination.

5.0 CONCLUSIONS

The TORNADO code is presently undergoing modification to develop site-specific tornado intensity distributions. Once the modification is completed, the code is expected to provide a comprehensive tool for developing a site-specific probabilistic tornado hazard curve at any site within the CONUS. The program allows easy modification of the model parameter values to account for new data and new interpretations of existing data.

6.0 REFERENCES

Abbey, R.F., Jr., “Research Efforts in Severe Storms Applied to Nuclear Reactors”, Second U.S. National Conference on Wind Engineering Research, Ft. Collins, CO, 1975.

Abbey, R.F. and Fujita, T.T., “The DAPPLE Method for Computing Tornado Hazard Probabilities: Refinements and Theoretical Considerations, “ 11th Conference on Severe Local Storms,” American Meteorological Society, Boston, 1979.

Fujita, T.T., ‘Workbook of Tornadoes and High Winds for Engineering Applications,” SMRP Research Paper 165, Department of the Geophysical Sciences, the University of Chocago, September 1978.

Fujita, T.T. and A.D. Pearson, “Results of FPP Classification of 1971 and 1972 Tornadoes,” Paper presented at the Eighth Conference on Severe Local Storms, 1973.

Garson, R.C., J.M. Catalan, and C.A. Cornell, “Tornado Design Winds based on Risk, ” Journal of the Structural Division, ASCE, Vol. 101, No.9, September 1975.

McDonald, J.R., “A Methodology for Tornado Hazard Probability Assessment,” Institute for Disaster Research, Texas Tech University, Lubbock, Texas, 1980.

McDonald J.R., “The Modified IDR Model - Short Course Notes,” Engineering for Extreme Winds: 1996, Texas Tech University, February 1996.

Ramsdell, J.V. and G.L.Andrews, “tornado Climatology of the Contiguous United States,” Pacific Northwest Laboratory, prepared for the US Nuclear Regulatory Commission, NUREG/CR-4461, May 1986.

Reinhold, T. and B. Ellingwood, “Tornado Damage Risk Assessment,” National Bureau of Standards, NUREG/CR-2944, 1982.

Twisdale, L.A. and W.L. Dunn, “Tornado Missile Simulation and Design Methodology,” Research Triangle Institute, NP-2005, Vol. 1, 1981.

Twisdale, L.A., W.L. Dunn and J. Chu, “Tornado Missile Risk Analysis”, EPRI Reports NP-768 and NP-769, Electric Power Research Institute, Palo Alto, 1978.

Twisdale, L.A. et al., “Probabilistic Analysis of Tornado Wind Risk,” ASCE Journal of Structural Engineering, Vol. 109, No. 2, February 1983.

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