Tornado Hazard Assessment and Effect of Structure Size

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ABSTRACT: The United States of America experiences more than 1000 tornadoes every year. Different from other large scale natural hazards such as earthquake and hurricane, the impact of a tornado is relatively small. The effect of structure size on tornado risk assessment is very important. Neglecting the structure size may lead to underestimation of tornado strike probability. This study presents the development of size-dependent tornado design maps for the United States. Using a stochastic tornado simulation model and a wind field model, tornado hazard maps for EF0 to EF5 wind speeds are developed for four different target structure sizes, namely point target, small (0.08 mi$^2$), medium (0.03 mi$^2$) and large (0.5 mi$^2$) circular targets. A model to quantify the relationship between tornado strike probability and target size is proposed. Using this relationship, the tornado hazard for a given location and structure size can be interpolated from the four size dependent hazard maps. This quantitative tornado hazard estimation method considering size effect can be used by engineers to determine the design wind speed.

1. INTRODUCTION
Unlike a hurricane, the footprint of a tornado is relatively small. While tornadic wind can be more violent than hurricane wind, due to the relatively small spatial coverage of tornadic wind, tornado is considered a low probability and high consequence event. To determine the risk of building stock exposed to potential tornado devastation, hazard maps which accurately estimate the tornado striking probability are deemed necessary (Boruff et al., 2003; Meyer et al., 2002; Sigal et al., 2000; Standohar-Alfano et al., 2014; Strader et al., 2016; Tan et al., 2010; Thom, 1963). Unlike hurricane or typhoons, tornados are short lived and localized events. Due to the unique characteristics of tornado risk, the effect of structure size plays an important role on risk calculation and damage assessment (S. Banik et al., 2007; S. Banik all, 2008; Ramsdell et al., 2007; L. A. Twisdale et al., 1983). Neglecting structure size may result in significant underestimation of tornado strike probability for structures with large area footprint or large-scale infrastructure. Therefore, size effect must be considered when evaluating tornado risk for critical infrastructure with a large spatial coverage area, such as school, hospital, nuclear power plant or petrochemical plant.

Tornado risk assessment has received considerable attention over the last few decades; however, size effect was neglected in many of the past studies (Meyer et al., 2002; Romanic et al., 2016; Standohar-Alfano et al., 2014; Strader et al., 2016; Tan et al., 2010). Size effect for one dimensional (1-D) line structures such as electric power transmission lines has been addressed by (S. Banik et al., 2008; L. A. Twisdale et al., 1983) Buildings and other structures with two dimensional (2-D) footprints cannot be modeled as line structures. For engineering design and risk evaluation purposes, high resolution tornado hazard maps which cover the whole continental Unites States are needed. The tornado maps developed in many past studies utilized reference domain with a 1-degree or higher grid resolution (one degree latitude is approximately 69 miles (111 km) apart). These coarse resolution hazard
maps may obscure the risk variation details in small region.

The main objectives of this study were: (1) to define and evaluate the tornado risk for 2-D structures, (2) to determine the appropriate grid spacing for high resolution tornado hazard maps, (3) to generate a series of tornado hazard maps for different intensity (EF scale) and structure sizes.

2. TORNADO DATA

To perform tornado hazard analysis, a database of past known tornado events is needed. The US National Oceanic Atmospheric Administration (NOAA) Storm Prediction Center (SPC) has compiled a database of past historical events, with more than 60,000 tornado recorded since 1953. The annually observed number of tornadoes, or annual occurrence rate, appears to be increasing. This could be due in part to the improvement of technology used for tracking tornadoes and the public awareness in reporting tornado incidents. Even with more than 60 years of data with over 60,000 known tornado events, there are many areas in the US that have not been hit by tornadoes or do not have any official record. Hence, it may not be feasible to estimate tornado risk solely based on past observations especially for high resolution risk assessment.

In order to estimate the risk for regions that have not been hit by historical tornadoes, a stochastic tornado track simulation method proposed by Fan et al. (2017) was applied in this study (see Chapter 2). A simulated tornado database with one million years of tornado tracks was generated using the stochastic simulation model. Each simulated track includes tornado parameters, such as intensity (EF scale), spawn location, touchdown time, path length and path width. The tornado track parameters are geographic dependent, meaning the parameters vary based on the tornado spawn locations.

3. TORNADO HAZARD FOR A POINT AND AREA

3.1. Tornado striking probability

Thom (1963) proposed a method to estimate the probability of tornado striking a point, and the equation is expressed as:

\[ P(V \geq v | Tor_i) = \frac{A_{si}}{A_R} \]  

where \( P(*) \) is the probability of tornado striking a point with maximum gust wind speed \( V \) greater than a given value \( v \). For a point target, \( A_{si} \) is defined as the tornado covered area with \( V \geq v \); and \( A_R \) is the tornado reference area or region. For the striking probability of circular area, the Eq. (1) mentioned above is still applicable, however \( A_{si} \) is redefined according to the target size and the tornado impact area (see Figure 1).

![Figure 1: Illustration of tornado striking probability](image)

In such a case, for a circular area (target) with radius \( r \), \( A_{si} \) is the tornado covered area plus the area painted in yellow. The yellow region is a region where tornado strike occurs if the center of the circular target lies within it. Based on this definition, \( r \) approaches zero as the target structure size is getting smaller. \( r \) equals to zero when the target is a point and \( A_{si} \) is equal to the area enveloped by the tornado track.

The above discussion is regard to the strike probability for a single tornado track. In order to assess the annual strike probability using the simulated tornado tracks database, the procedure is revised as follow. If \( v = 65 \text{ mph} \), which is the lower bound wind speed of an EF0
tornado. The probability of a point not affected by a tornado strike is defined as:

$$P(V < 65 \text{ mph} \mid Tor_i) = \frac{A_R - A_{si}}{A_R} \tag{2}$$

Probability of tornadoes not striking a point for year $j$ ($P_{j,NS}$) is:

$$P_{j,NS} = P_j(V < 65 \text{ mph} \mid Tor_1) \times P_j(V < 65 \text{ mph} \mid Tor_2) \times \ldots \times P_j(V < 65 \text{ mph} \mid Tor_n) \tag{3}$$

Probability of tornado striking a point for year $j$ ($P_{j,S}$) is:

$$P_{j,S} = 1 - P_{j,NS} \tag{4}$$

Then, the mean annual probability of tornado striking a point with maximum gust wind speed $V \geq v$ is:

$$P(V \geq v \mid Tor_i)_{\text{Annual}} = \frac{\sum_{j=1}^{N_{\text{year}}} P_{j,S}}{N_{\text{year}}} \tag{5}$$

where $N_{\text{year}}$ is the total simulation years and $N_{\text{year}}$ equals to one million years in this study.

### 3.2. Reference domain for the uniform hazard

The tornado hazard varies depending on geographic location. For instance, the annual occurrence rate for a location in tornado valley is expected to be higher than a location along the eastern coast of the US. While the tornado hazard may vary in a large geographic region, it is assumed that the tornado risk remain uniform (or approximately uniform) within a small region. The most appropriate reference domain size (i.e. grid spacing for hazard map) should accurately reflect the spatial variation of local tornado hazard. A large reference domain can cause “oversmoothed” effect for hazard map which obscures much of the risk variation details in small region. To determine the optimal domain size, tornado striking probabilities for a point structure are

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**Figure 2**: Tornado striking probability for a point at (A) Birmingham, (B) Oklahoma City, (C) San Antonio, (D) Bozeman.
evaluated at four locations with a varying circular reference domain radius range from 65.5 feet to 25.5 miles.

The four locations were selected from different regions of the United States based on the tornado risk level. The first two locations were selected in high risk region, Birmingham located in the north central region and Oklahoma City located in the Southern Great Plains region (Figure 2, (A) and (B)). The other two locations were selected in moderate or low risk region, San Antonio located in the South Central region and Bozeman located in the North-western United States (Figure 2, (C) and (D)). At each location, tornado strike probabilities for a point-like target with varying reference domain size were calculated using Equation 1. In high risk region, strike probability of weak (EF0 and EF1) and strong (EF2-EF3) tornadoes are not very sensitive to the change in domain size, mainly because there are sufficient number of simulated tornado events in that region. However strike probability of violent tornadoes (EF4-EF5) may fluctuate if the domain radius is less than 10 miles because the simulated database (1,000,000 years) is not long enough to capture this kind of rare event in such a small region.

Similar patterns were also observed for moderate and low risk regions. If the reference domain radius is less than 10 miles, the estimated annual strike probabilities of EF3 to EF5 tornadoes for San Antonio, Texas (Figure 2, C) and Bozeman, Montana (Figure 2, D) show variation. In order to maintain a balance between computation cost and accuracy, a 15-mile radius is selected as the reference domain with approximately uniform hazard and the grid points for the tornado hazard maps are spaced 15 miles apart.

4. TARGET SIZE EFFECT

It has been determined that the tornado hazard is approximately uniform within a 15-mile radius. However, the risk of a structure may vary depending on the size of the structure even within a 15-mile uniform hazard region. To investigate the size effect of structure on tornado risk, seven different target domain (structure) sizes ranging from 0.025 mi to 0.8 mi (Table 1). The area of the largest target size is about 1024 times larger than the smallest target. All target domains are assumed located near Oklahoma City, and the location is shown in Figure 3 (A). The Will Rogers World Airport (OKC) which has a footprint of about 0.47 mi² and the Moore High School which has a footprint of about 0.025 mi² (688,596 ft²), are used to establish the domain sizes considered in this study. The size of the OKC airport is between target 5 (0.63 mi²) and target 6 (1.22 mi²), while the size of the Moore high school is in between target 2 and target 3.

The tornado risk for these 6 targets have been investigated using the method in section 3.1. Figure 3 (B) clearly shows that tornado hazard for nonzero structure size target can be several orders of magnitude higher than that for a point-like

Figure 3: Target location and normalized annual probability of exceedance for wind greater than 111 mph.
target. For instance, the annual probabilities of exceeding a 65 mph wind (lower bound wind speed of EF0 tornado) are about $2.1 \times 10^{-2}$ and $7.5 \times 10^{-4}$ for a target of 2.43 mi$^2$ and a point-like target, respectively. The MRI for observing tornadoes with wind speed exceeding 65 mph are 47 years and 1323 years for a target of 2.43 mi$^2$ and a point-like target, respectively. The increase in the probability of exceedance for a structure with a finite size target is highly dependent on the size. Such a relationship can be expressed using a power function:

$$y = ax^b + c$$

where $a$ serves as a scaling factor; $b$ is the exponent; $c$ is the $y$ intersection. The fitted curve is plotted in Figure 3B. It shows that for a small target with an area of about 0.0024 mi$^2$ (67,000 ft$^2$), the strike probability is about 2 times higher than a point-like structure. For large target with an area of 2.43 mi$^2$ ($6.7 \times 10^7$ ft$^2$), the strike probability is about 30 times higher than a point-like structure.

5. METHODOLOGY

5.1. Study Domain

Figure 4 shows the grid points used for mapping the US tornado hazard. A 15-mile spacing grid spanning from $67^\circ$ W to $124^\circ$ W, and $25^\circ$ N to $49^\circ$ N is utilized to cover the entire continental US with a total of 17,646 points. A more detailed zoom-in view for Oklahoma City is also presented in Figure 4. As illustrated in the figure, a 15-mi radius circular area is used to generate the hazard curve for each grid. Note that this approach allows overlapping of region with neighboring grid points.

Table 1: Target size applied in hazard maps

<table>
<thead>
<tr>
<th></th>
<th>Small Target</th>
<th>Medium Target</th>
<th>Large Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area (mi$^2$)</td>
<td>$\approx 0.0096$</td>
<td>$\approx 0.038$</td>
<td>$\approx 0.62$</td>
</tr>
<tr>
<td>Area (km$^2$)</td>
<td>$\approx 0.020$</td>
<td>$\approx 0.077$</td>
<td>$\approx 1.3$</td>
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</tbody>
</table>

5.2. Target Size

According to the study of Twisdale (1983) and the discussion in section 4, The effect of structure size plays an important role in tornado wind speed risk analysis. In order to consider the size effect, three circular targets with different sizes are used in the mapping of tornado hazard. The area of the first (small) target is about 0.0096 mi$^2$, the area of the second (medium) target is about 0.038 mi$^2$, and the area of the third (large) target is about 0.62 mi$^2$. For easy reference, these three targets are termed small target, medium target and large target, respectively (Table 1).

Figure 4: Location of circle centers and the extent of 15 mi sample circles.

Figure 5: Clemson Elementary School (SC), Area $\approx 0.01$ mi$^2$ (A); Greenville Haywood Mall (SC), Area $\approx 0.027$ mi$^2$ (B); Eastman chemical plant in Kingsport (TN), Area $\approx 0.64$ mi$^2$ (C).
The three different target sizes are selected to represent typical damages observed in past tornado damage survey reports to different types of infrastructure or buildings (Figure 5). The small target used in the mapping is selected to represent the tornado hazard for typical schools or hospitals. The medium target is selected to represent typical big-box retails, commercial buildings or shopping malls. Finally, the large target is used to represent larger infrastructure such as airports, electrical power plants, petrochemical plants and other manufacturing facilities.

5.3. Analysis Procedures

1. Load the tornado track database. The simulated tornado database includes 1,000,000 years of simulation ($N_{year}$). The stochastic simulation procedure is explained in Chapter 2.

2. For each study domain $j$ ($j = 1,2,3,... N_{domain}$), establish the domain envelope and area ($A_{r,j}$).

3. For simulation year $t$, determine the total number of candidate tornados that affect the domain $j$ by detecting overlapping between each tornado footprint and the domain area.

4. For each selected tornado, calculate the tornado impact area $A_{si}$ and the non-strike probability of each tornado.

5. Save the non-strike probability of each impacted tornado based on the equations discussed previously and repeat step 4 until $i = N_{tor,jt}$ (i.e. loop through all candidate tornadoes).

6. Calculate and record the tornado strike probability of year $t$ for domain $j$ according to the equations previously and repeat steps 3 to 5 if $t \leq N_{year}$.

7. Calculate and record the tornado annual strike probability of domain $j$, and repeat steps 2 to 6 if $j \leq N_{domain}$.

6. RESULT AND DISCUSSION

Tornado strike probability for point and area targets are estimated using the simulated tornado database (1,000,000 simulation years) at every grid point in the United States. A hazard map for a given target size is then created for each of the five tornado intensity levels (EF0 to EF5). The tornado hazard maps for a point target and large targets are shown in Figure 7.

Figure 7 presents the contour maps of annual tornado strike probability for point-like structure (e.g. single family homes) and large circular target (e.g. airport). Figure 7 (A shows the annual probability (P) of experiencing EF0 and higher wind speed ($V \geq 65 mph$) for different target sizes. The high risk regions (P = $10^{-3}$ to $10^{-2}$) of
experiencing EF0 and greater tornadoes are located in the Tornado Alley (extends from northern Texas, Oklahoma, Kansas, into Nebraska) and Dixie Alley (stretches from eastern Texas and Arkansas across Louisiana, Mississippi, Tennessee, Alabama, Georgia, to upstate South Carolina, and western North Carolina). The low risk tornado regions (P = 10^{-9} to 10^{-10}) for EF0 and greater tornadoes are observed in the Western US, between the Rocky Mountains and the West Coast of the US.

The annual strike probability increases with increasing target size. For instance, the probability of seeing EF0 and greater tornadoes in high risk regions increases by an order of magnitude when compared between a point target (P = 10^{-3} or MRI = 1000 years, Figure 7A) and a large target (P=10^{-2} or MRI = 100 years, Figure 7D). Although the West Coast of the United States generally experiences only weak tornadoes (EF0 to EF3) when compared to the mid and eastern US. In the western US, especially California, the annual probability of experiencing tornadoes (i.e.
EF0 and greater) for a large target can be as high as $10^{-3}$ (MRI of 1000 years, Figure 7D).

7. CONCLUSIONS
The study investigated the spatial distribution of annual probability of exceedance of EF0 to EF5 tornadoes considering the structure size effect. Site- and structure size-specific tornado hazard maps were created using a simulated tornado database. It has been shown that the strike probability of tornadoes increases with increasing target size. Except for in Tornado Alley and Dixie Alley, weak tornadoes (EF0 and EF1) govern the tornado hazards of Western and Eastern coasts of the United States. The annual strike probability of weak tornadoes is estimated to be in the order of $10^{-2}$ in high risk region. The high risk regions for strong tornadoes (EF2 and EF3) are bounded by Rocky Mountains and Appalachian Mountains, and the highest strike probabilities in these regions are about $10^{-3}$ to $10^{-4}$. Violent tornadoes (EF4 and EF5) are rare events which have a very low probability of occurrence in regions outside of Tornado Alley, Dixie Alley, and Midwest with the highest annual occurrence probability of approximately $10^{-5}$ to $10^{-6}$.

8. REFERENCES