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Original Article

An Evaluation Method for Tornado Missile Strike Probability with Stochastic Correlation

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ABSTRACT

An efficient evaluation method for the probability of a tornado missile strike without using the Monte Carlo method is proposed in this paper. A major part of the proposed probability evaluation is based on numerical results computed using an in-house code, Tornado-borne missile analysis code, which enables us to evaluate the liftoff and flight behaviors of unconstrained objects on the ground driven by a tornado. Using the Tornado-borne missile analysis code, we can obtain a stochastic correlation between local wind speed and flight distance of each object, and this stochastic correlation is used to evaluate the conditional strike probability, $Q_V(\mathrm{r})$, of a missile located at position r, where the local wind speed is V. In contrast, the annual exceedance probability of local wind speed, which can be computed using a tornado hazard analysis code, is used to derive the probability density function, $p(V)$. Then, we finally obtain the annual probability of tornado missile strike on a structure with the convolutional integration of product of $Q_V(\mathrm{r})$ and $p(V)$ over V. The evaluation method is applied to a simple problem to qualitatively confirm the validity, and to quantitatively verify the results for two extreme cases in which an object is located just in the vicinity of or far away from the structure.

1. Introduction

Tornadoes can produce airborne missiles because of their high-speed wind, and missile impact on structures, systems, and components of a nuclear power plant could lead to physical and functional damage with possible deviation from normal plant conditions. To understand such risk induced by tornado missiles, we need to evaluate not only the degree of potential damage incurred but also the probability of the occurrence. In the USA, probabilistic evaluation of tornado missile hazard and fragility was intensively studied in the 1980s. In particular, the Electric Power Research Institute developed a probabilistic computer code for tornado missile risk analysis, TORMIS, to compute the damage probability and its uncertainty range [1–3]. In recent years, Tornado Missile Strike Calculator has been developed by Westinghouse Electric Company (Windsor, CT, USA) [4], which has demonstrated that Tornado Missile Strike Calculator is capable of yielding

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reasonable results comparable to those of TORMIS. In these tools, the probability of a missile strike is computed using the Monte Carlo method with the running of an enormous number of simulation cases.

The objective of this study is to formulate an efficient evaluation method for the probability of a tornado missile strike without using the Monte Carlo method. In this study, the tornado missile liftoff and flight behaviors are computed by our in-house software, named Tornado-borne missile analysis code (TONBOS) [5,6], which enables us to reasonably compute dynamic behaviors for unconstrained objects placed on the ground, such as automobiles. The numerical results are used to obtain a stochastic correlation between the local wind speed at 10 m above ground level (AGL), V, and the flight distance, L; with these pieces of information, the conditional strike probability can be efficiently computed. In contrast, the annual exceedance probability of local wind speed, computed with a tornado hazard analysis code, is used to obtain the probability density function of the local wind speed. Then, the annual probability of tornado missile strike on a structure is computed using the convolutional integration of both ingredients [7]. In the following section, we will fully explain the evaluation scheme for annual missile strike probability. As a numerical example, the method is applied to automobiles on the ground to compute the annual strike probability on a cylindrical structure, as explained in Section 3. We shall discuss the validity of the results and the effects of tornado pressure distribution on the flight behavior in Section 4 and draw conclusions in Section 5.

2. Materials and methods

2.1. Overall framework

Fig. 1 shows the overall framework of the proposed evaluation method. First, a correlation between local wind speed, V, and flight distance, L, is obtained from the numerical results of TONBOS and is used to compute the conditional probability density function, $S_V(L)$, with respect to the flight distance under a specific local wind speed condition. Then, conditional strike probability, $Q_V(\mathrm{r})$, can be obtained via convolutional integration of the product of $S_V(L)$ and $q(\mathrm{r},L)$ over L, where $q(\mathrm{r},L)$ is the strike probability of an object (possible missile) at position r, whose flight distance is L. By contrast, the annual exceedance probability of local wind speed, $H(V)$, computed with a tornado hazard analysis code, e.g., Tornado Wind Speed Hazard Model for Limited Area (TOWLA) [8], is used to obtain the probability density function, $p(V)$, by differentiation of $H(V)$ with respect to V. Then, we can finally obtain the annual probability of tornado missile strike on a structure, $P_h(\mathrm{r})$, with the convolutional integration of the product of $Q_V(\mathrm{r})$ and $p(V)$ over V.

The basic equations used in TONBOS for the missile liftoff and for the flight model are explained in Subsection 2.2, whereas those for the tornado wind field model are provided in Subsection 2.3. In Subsection 2.4, it is explained how we can obtain the conditional probability density function, $S_V(L)$, that represents the stochastic correlation between local wind speed V and flight distance L. In Subsection 2.5, we discuss the evaluation scheme for annual missile strike probability, particularly how the tornado hazard curve, $H(V)$, is combined with the conditional strike probability.

2.2. Missile liftoff and flight model of TONBOS

A user of TONBOS can select either the Fujita model (DBT-77) [9] or the Rankine vortex model [10,11] as a tornado wind field model, while motion of objects in flight is modeled with 3 degrees-of-freedom translational equations in which aerodynamic drag force and gravity are taken into account [10,11]. The unique feature of TONBOS is that objects are assumed to be subject to lift force near the ground; this force is generated by asymmetric air flow around objects because of the ground effect.

2.2.1. Liftoff model

Objects on and near the ground are assumed to be subject to lift force generated by asymmetric air flow because of the

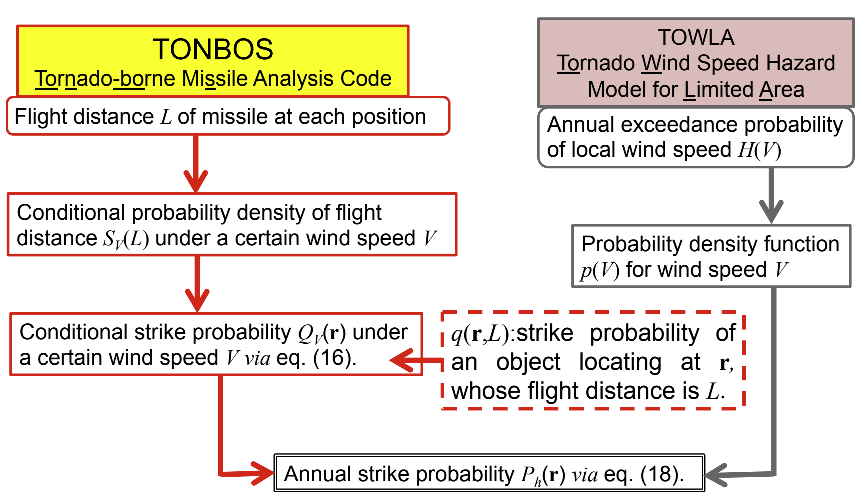

Fig. 1 – Computational flow of annual strike probability.