Computation of Annual Strike Probability of a Wind-borne Tumbling Missile using TOMAXI

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14th International Conference on Probabilistic Safety Assessment and Management (PSAM 14)
16-21 September, 2018, UCLA, Los Angeles, CA

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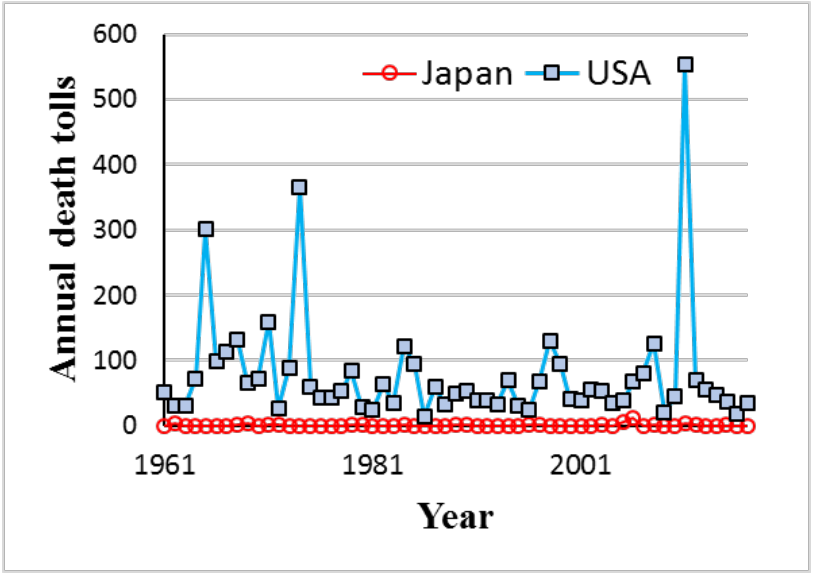
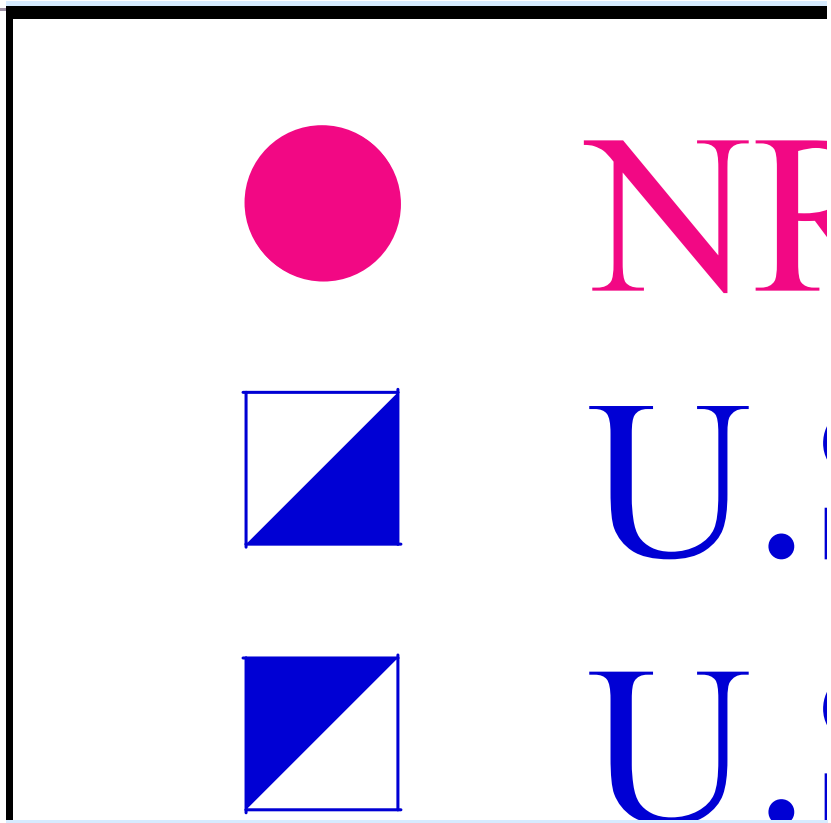
Background of this study



average (1961-2017)

0.72/year in Japan vs. 77.4/year in USA

(38.1/year, adjusted for area and population density of Japan)



The regulations for tornado missile

Reasons of the seemingly excessive conservatism

<table>
<tr><th>items</th><th>Japan</th><th>USA</th></tr>
<tr><td>Tornado intensity scale</td><td>The meteorological agency has officially started adopting the Japanese Enhanced Fujita (JEF) scale, but Nuclear Regulatory Authority (NRA) of Japan has not adopted JEF-scale for tornado design.</td><td>Enhanced Fujita (EF) scale is used.
<table>
<tr><th>region</th><th>Reg. Guide 1.76 (AEC, 1974)</th><th>Reg. Guide 1.76 Rev.1 (2007)</th></tr>
<tr><td>Ⅰ</td><td>161 m/s</td><td>103 m/s</td></tr>
<tr><td>Ⅱ</td><td>134 m/s</td><td>89 m/s</td></tr>
<tr><td>Ⅲ</td><td>107 m/s</td><td>72 m/s</td></tr>
</table></td></tr>
<tr><td>Evaluation method</td><td>Fully deterministic approach is used in determining design tornado missile speed.</td><td>Probabilistic aspects are partly considered in determining design tornado missile speed.</td></tr>
</table>

Objectives and methods of this study

Objectives

to evaluate probabilistic aspects of tornado-borne missiles, in particular, annual strike probability of automobiles.

Methods

by combining three evaluation codes:

1. tornado wind hazard analysis code (TOWLA),
2. tornado-borne missile ballistic simulation code (TONBOS),
3. annual strike probability evaluation code (TOMAXI).

Review of Previous Methodologies for Tornado Missile Strike Probability

Code name	Developer	Main features
TORMIS	EPRI (Currently, Applied Research Associates, Inc. maintains the up-to-date version)	【method】Monte Carlo method (tornado path etc.) 【note】approved for use by the NRC in 1983, and applied to real sites for tornado missile protection exemptions
TMSC (Tornado Missile Strike Calculator)	Westinghouse Electric Company	【method】Monte Carlo method (tornado path etc.) 【note】EXCEL-based code (Visual Basic for Application), NOT approved by NRC yet
TMRE (Tornado Missile Risk Evaluator)	Nuclear Energy Institute (NEI)	【method】Scaling approach: Standard values of Missile Impact Probability (MIP) are calculated based on TORMIS results (EPRI Report NP-768, 1978), and applied to generic evaluations by multiplying it with a target area. 【note】NRC Contractor report (*) says, "The scaling approach was found defensible, but additional verification and adjustments are needed in several areas. "

*Southwest Research Institute, Analysis of Missile Impact Probability for Generic Tornado Hazard Assessment, 2016.

Basic idea employed in TOMAXI code

Annual missile strike probability: p_h

$p_h = P \cap Q$ (conceptional expression)

P : tornado attack frequency (1/year)

Q : conditional missile strike probability, if tornado attacked.

Take wind speed dependences of P and Q into account

Annual strike probability for a target locating at $\mathbf{r}$, $p_h(\mathbf{r})$,

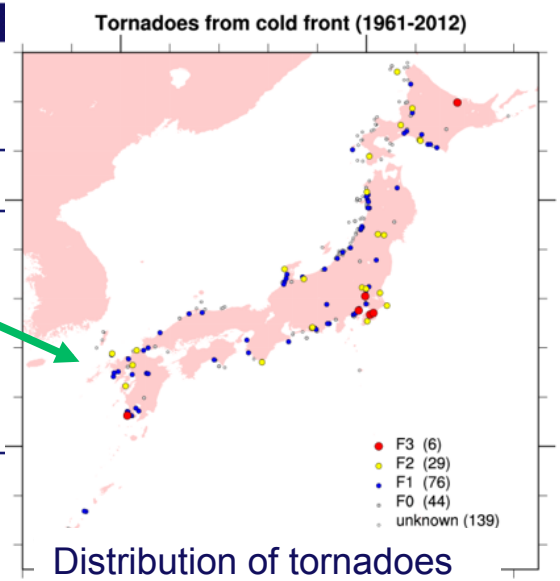
$P(V)$: Probability density function of local wind speed, V ($y^{-1}/(m/s)^{-1}$)

$Q_V(\mathbf{r})$: Conditional strike probability for local wind speed, V

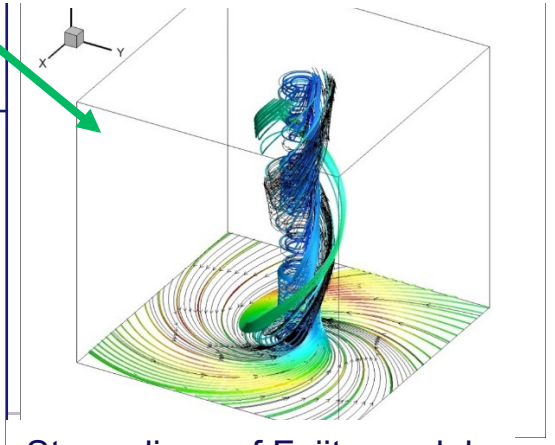
$H(V)$: Annual exceedance probability of local wind (y^{-1})

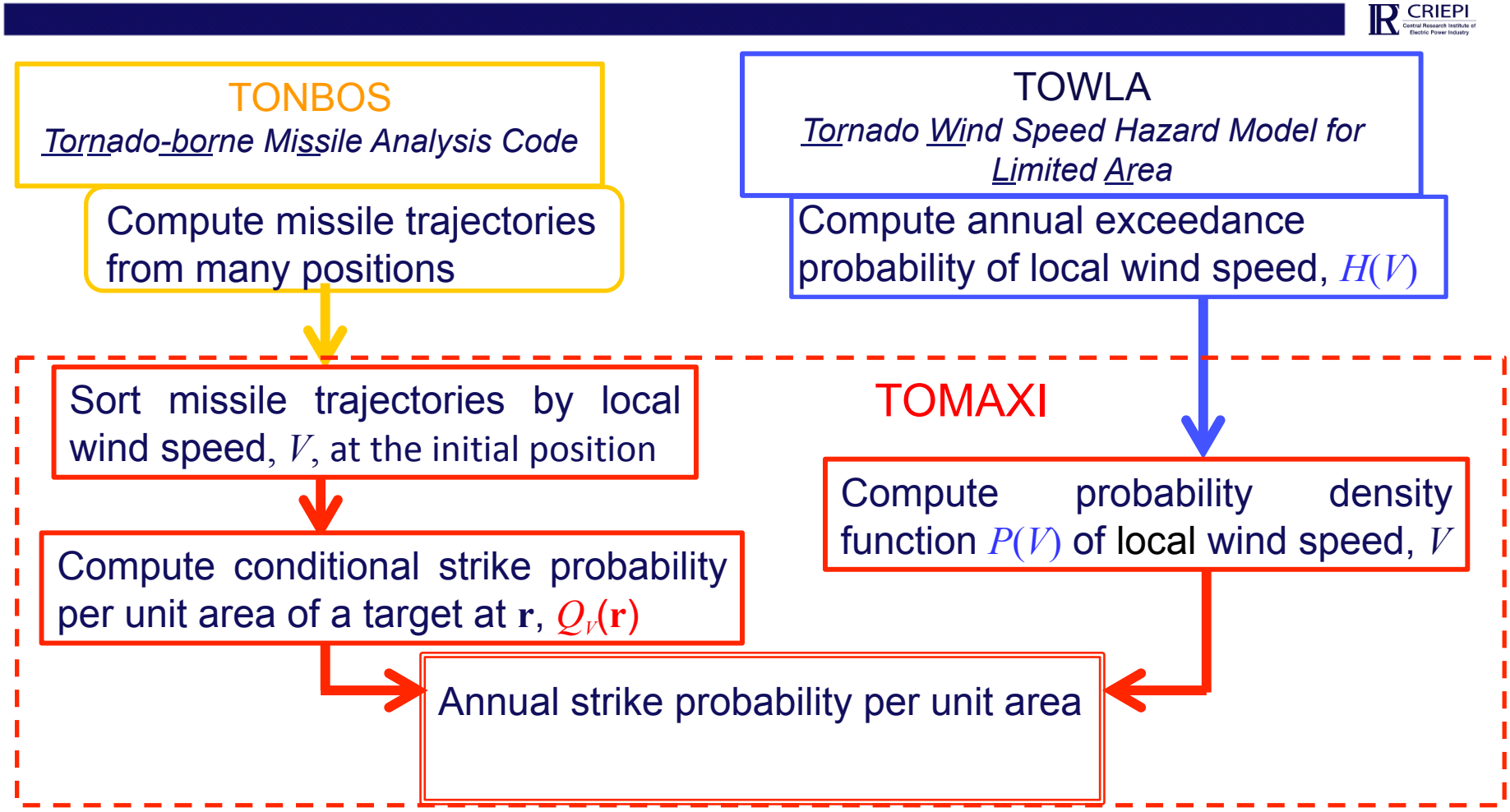
In-house computer codes employed

Code	function	note
TOWLA	compute tornado wind hazard curve, $H(V)$, using meteorological database	● non-uniform distribution of tornadoes in Japan (high density along the coast)
TONBOS	compute trajectories and speed of tornado-borne missiles	● Random orientation model /tumbling model of missile ● Fujita model for wind field
TOMAXI	Compute **spatial distribution of annual missile strike probability** of a missile	● Target is horizontal or vertical plate at arbitrary position. ● **Statistical isotropy of tornado path direction is assumed.**



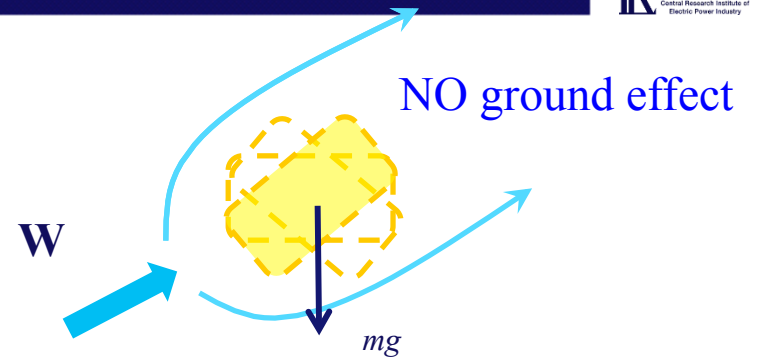
Distribution of tornadoes


Streamlines of Fujita model

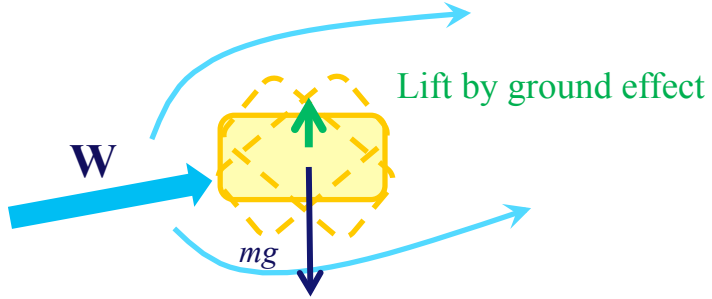

TONBOS
Tornado-borne Missile Analysis Code
Compute missile trajectories from many positions
TOWLA
Tornado Wind Speed Hazard Model for Limited Area
Compute annual exceedance probability of local wind speed, $H(V)$
TOMAXI
Sort missile trajectories by local wind speed, V, at the initial position
Compute probability density function $P(V)$ of local wind speed, V
Compute conditional strike probability per unit area of a target at $\mathbf{r}$, $Q_V(\mathbf{r})$
Annual strike probability per unit area

Unique feature of TONBOS (1)

Ground effect on lift force

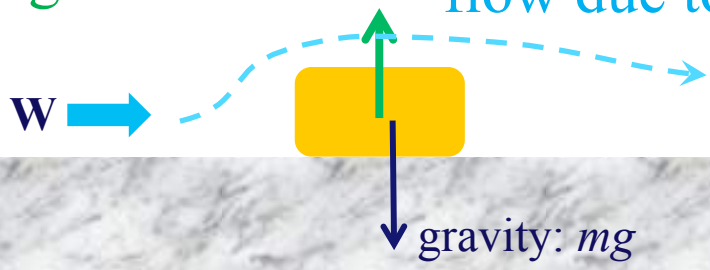


near-ground region



Lift force by ground effect

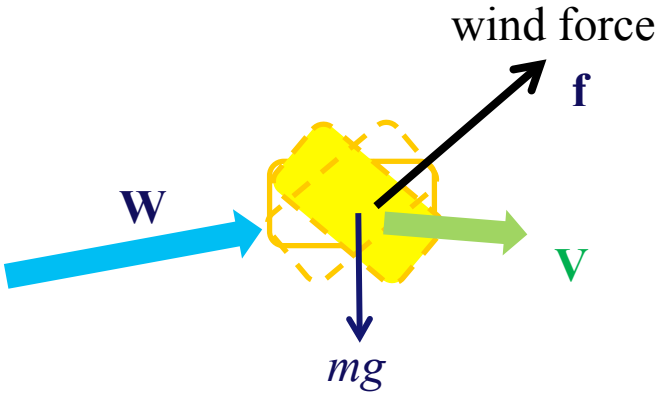
Unsymmetrical flow due to ground

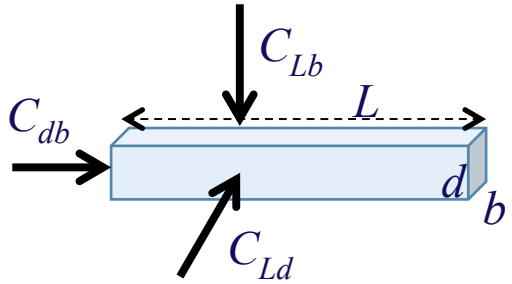


Unique feature of TONBOS (2)

Random orientation update interval

STEP_0. set q=0
STEP_1. integrate the above eq. in time
STEP_2. update object orientation if q> p
and go to STEP_0, else STEP_1.





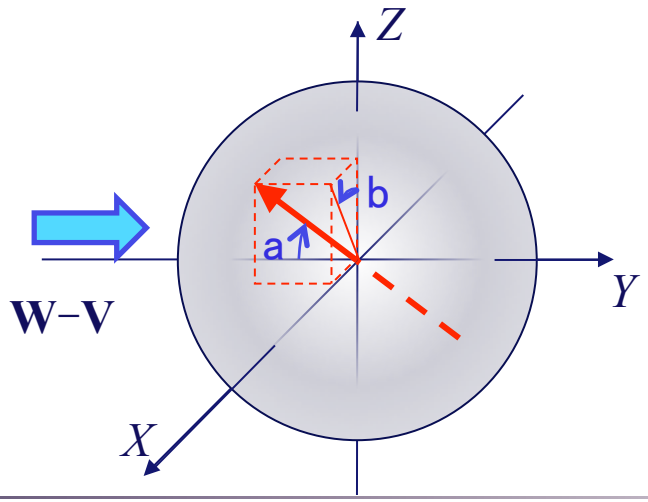
Coefficients of aerodynamic forces depending on orientation

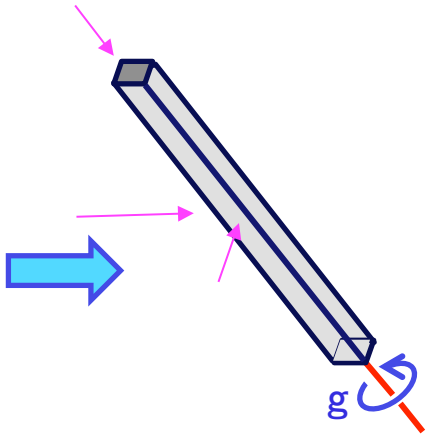
drag coeff.

lift coeff.

side force coeff.

cross-flow theory





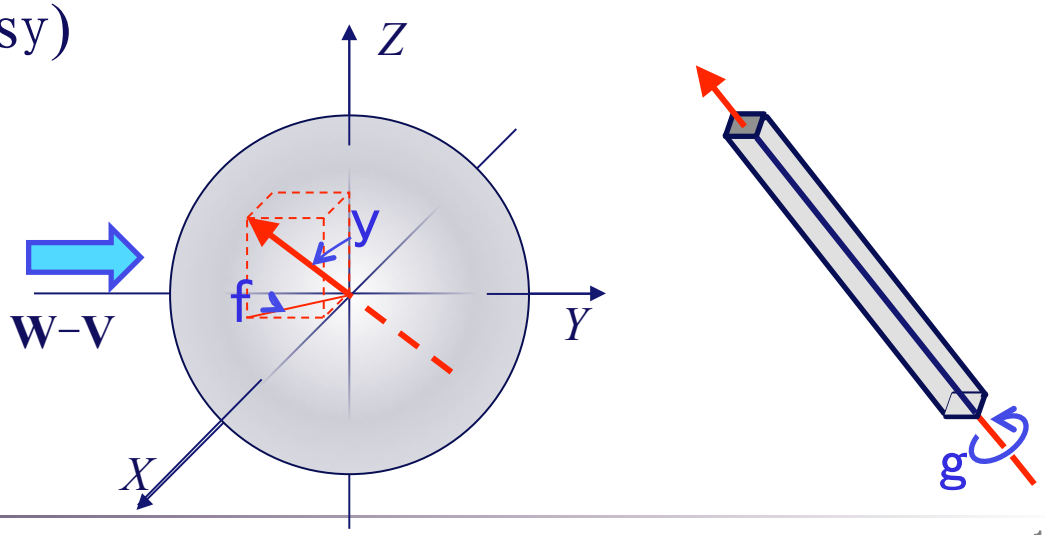
Random orientation model (Twisdale & Vickery, 1992)

$\gamma = \cos^{-1}(1-2x_1)$, $\phi = p(2x_2-1)$, $\omega = 2px_3$

where x_1, x_2, x_3 : random number between 0 and 1

Orientation vector, **L** is defined by angles γ and ϕ.

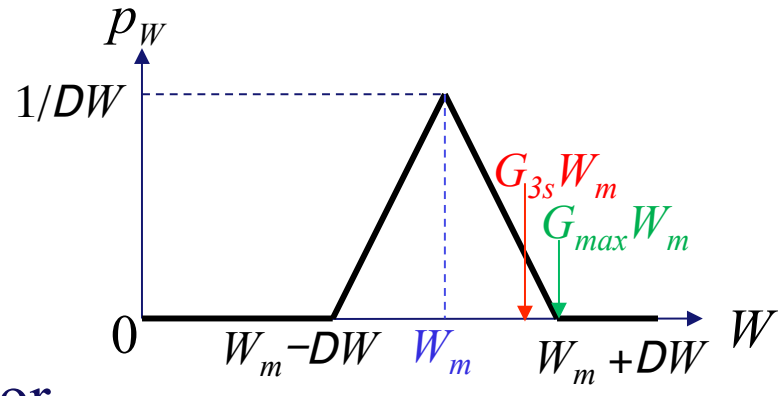
L $=(\sin\phi \sin\gamma, -\cos\phi \sin\gamma, \cos\gamma)$



Unique feature of TONBOS (3)

Random wind speed fluctuation

where x_a, x_b : random number between 0 and 1



where G_{3s} : 3s gust factor

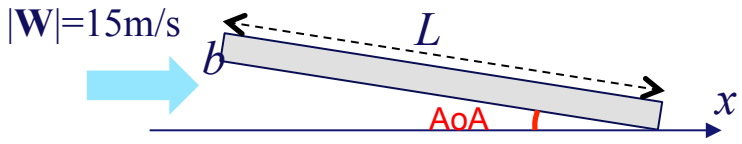
G_{max} : maximum gust factor

Validation of aerodynamic & flight model

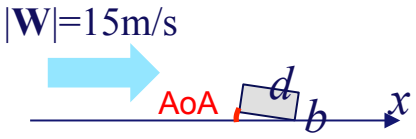
[22] Lin, N., “Simulation of windborne debris trajectories”, Master of Science thesis, Dept. of Civil Engineering, Texas Tech Univ., Lubbock, Texas, 2005.

wind tunnel experiment

AoA=0°, 15°, 45°



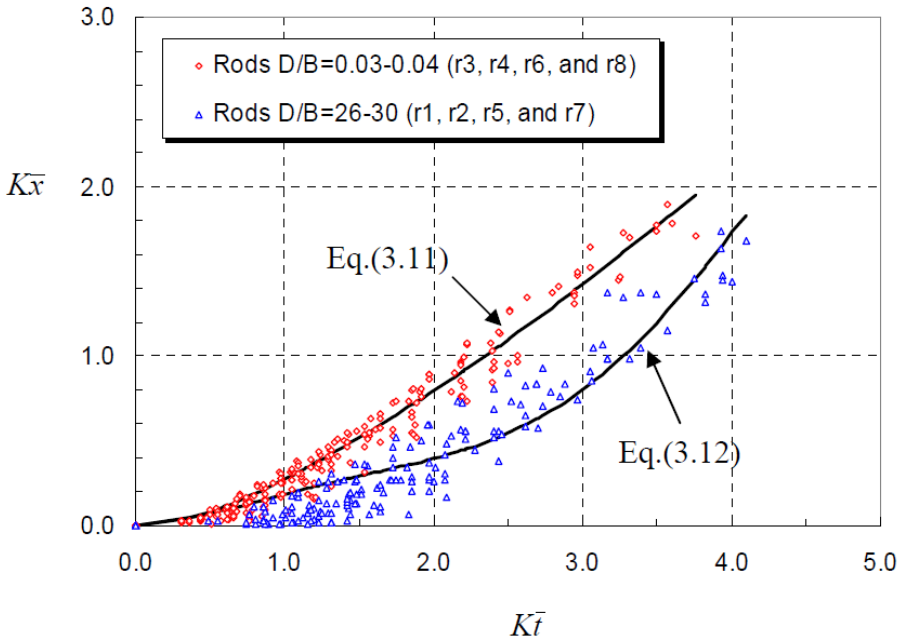
parallel initial condition

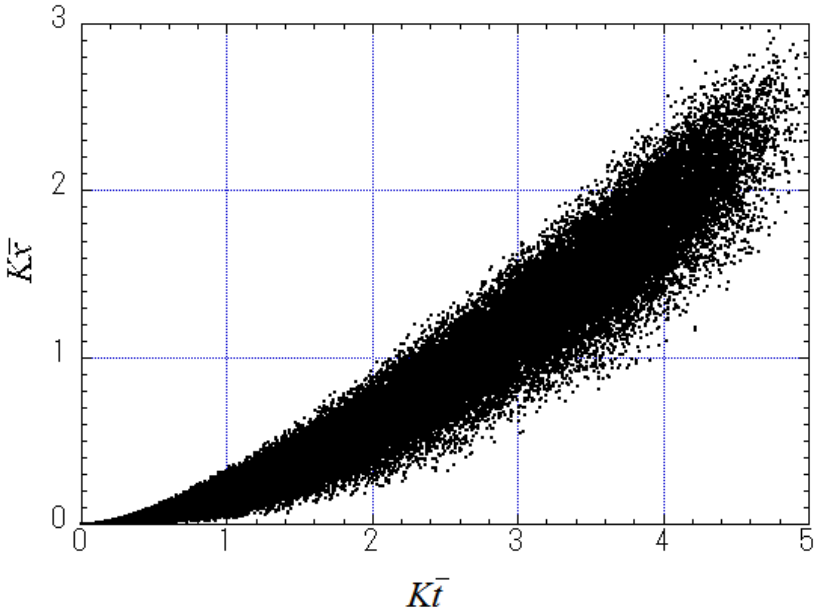


perpendicular initial condition

Horizontal displacement, x, is recorded with time, t, and non-dimensionalized.

Experimental and numerical results

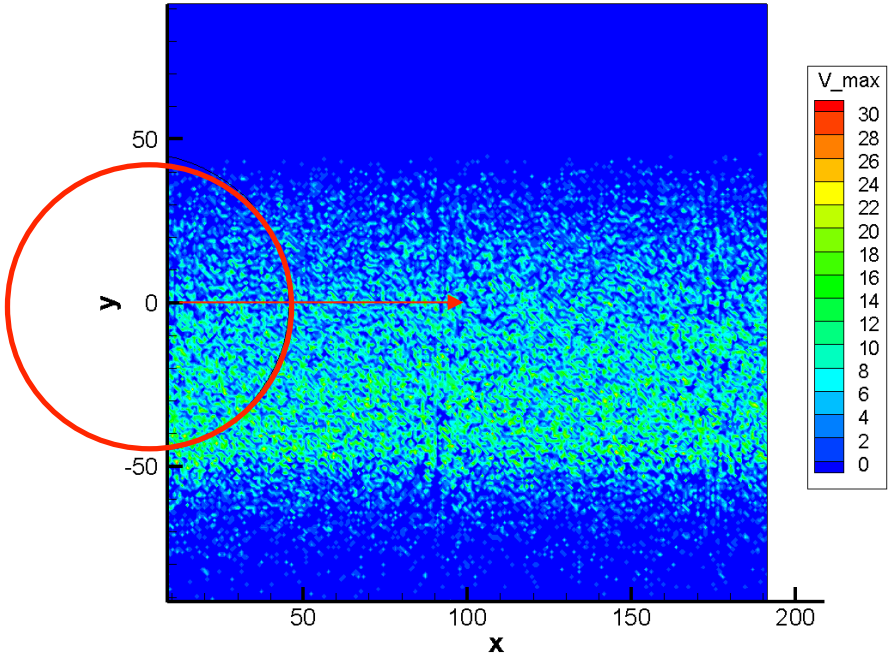




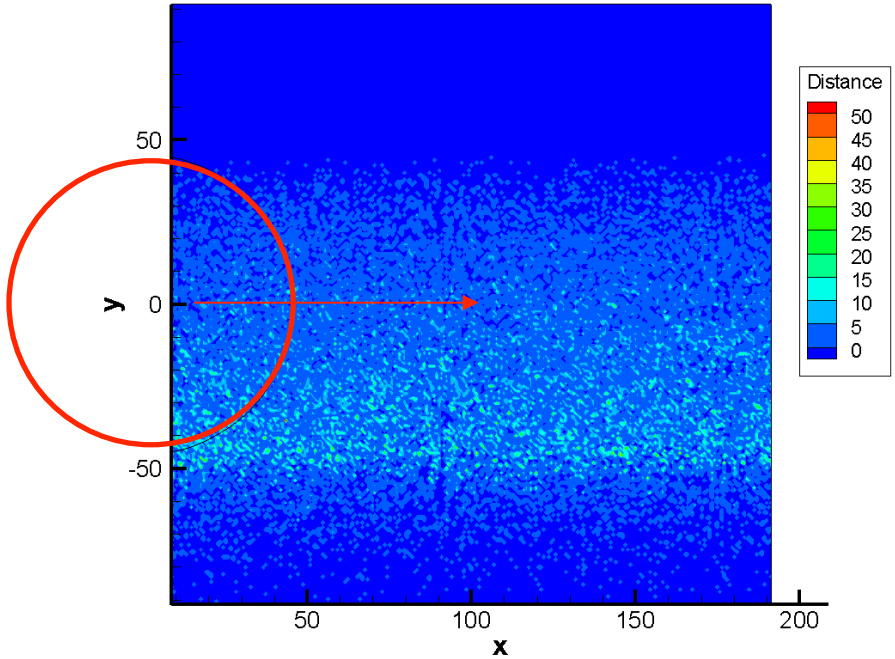
Experimental results by Lin [22]

Numerical results by the present model

Distribution of missile speed and flight distance

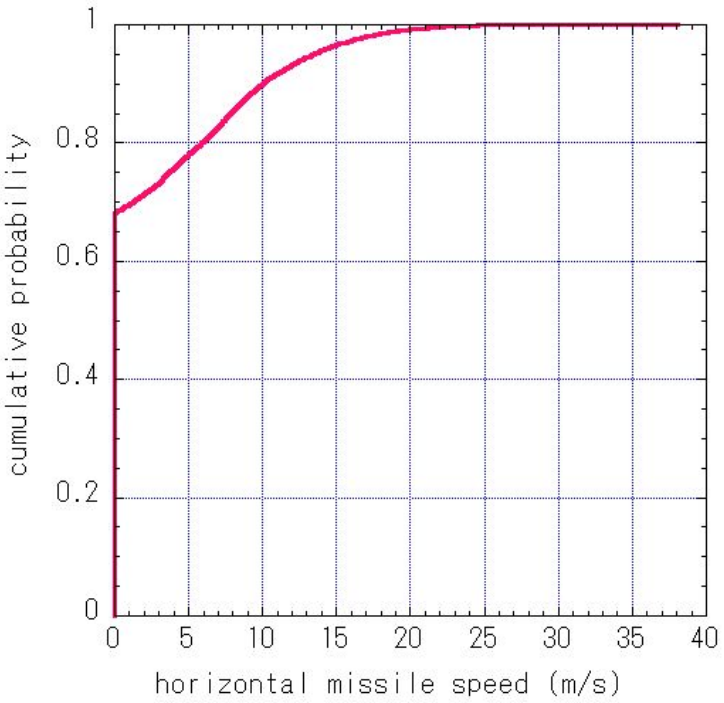


Maximum horizontal speed [unit: m/s]

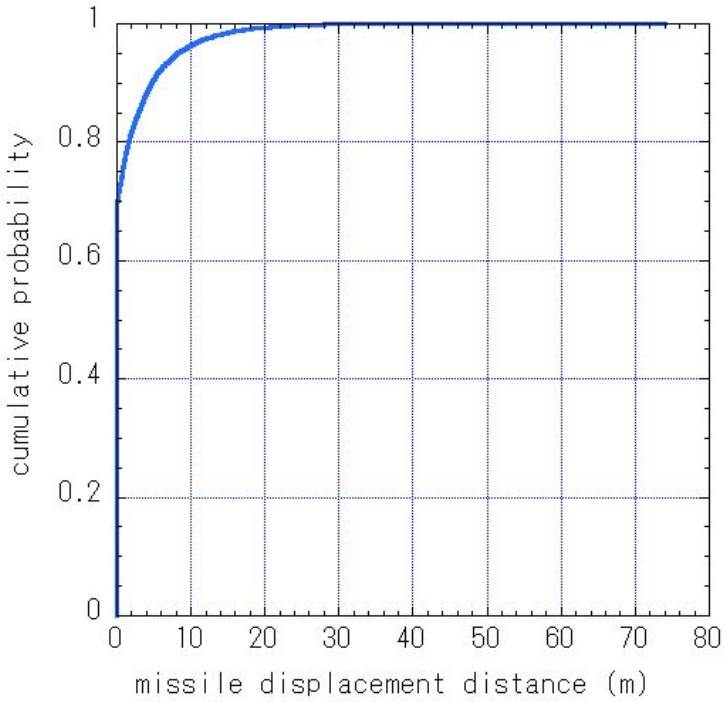


Flight displacement distance [unit: m]

Cumulative probability of missile speed and distance

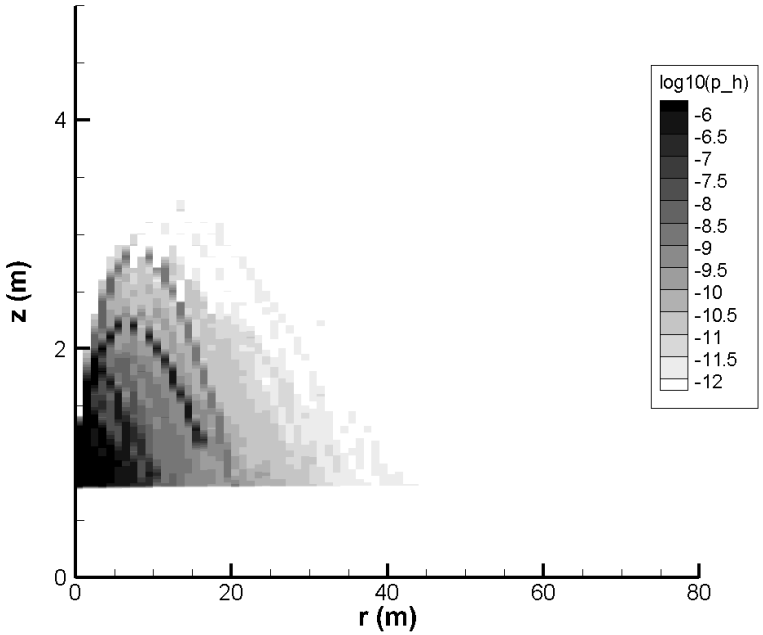


Cumulative probability of maximum horizontal speed

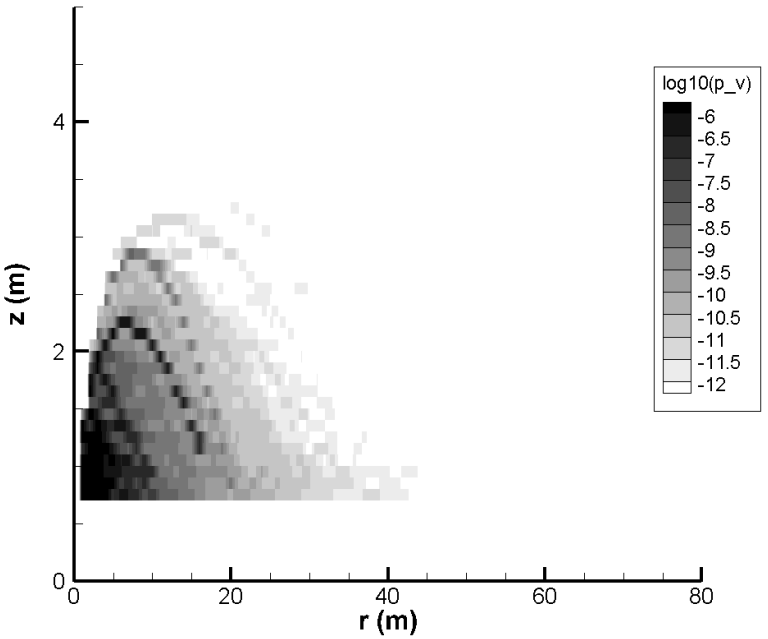


Cumulative probability of flight displacement

Annual automobile strike probability



Strike probability for horizontal plate of unit area



Strike probability for vertical plate of unit area

Conclusion

- The velocity fluctuation model and random orientation model are newly implemented in TONBOS (ver.4) to take the probabilistic features into account.
- An evaluation method for tornado missile strike probability has been developed by assuming statistical isotropy of tornado path direction (without fully employing Monte Carlo method).
- As an example, annual strike probability of an automobile on the ground under EF5 tornado condition has been demonstrated.

Thank you for your attention!