KOGEI 東京工芸大学 TOKYO POLYTECHNIC UNIVERSITY

一般財団法人 大成学術財団 The Taisei Foundation

2021/10/29
第3回 研究成果発表会

日本型竜巻の新しい工学的竜巻モデルの開発

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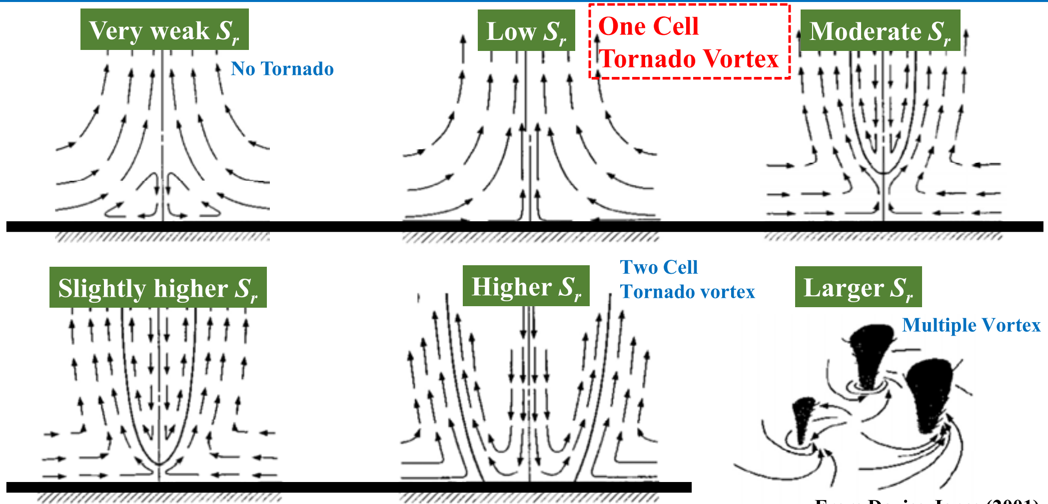
Conceptual tornado structure: Effect of Swirl Ratio, V_{max}/U_{max}



From Davies-Jones (2001)

Introduction

• **Tornadoes** are the **most devastating meteorological natural hazards** and are generally defined as violently rotating columns of air, pendant from the base of a convective cloud and often observable as funnel cloud attached to a cloud base.

• To evaluate tornado-induced loads precisely, **three loading** cases should be considered.

i) First is time-varying **surface pressures** over the buildings / structures

ii) Second is loads due to **pressure differences**

iii) Last is loads induced by **wind-borne debris**

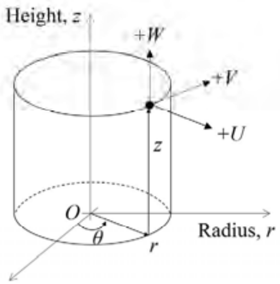
Introduction

• Since tornadoes move fast and their courses are unpredictable, the study of tornadoes from **direct measurements** has been always **difficult and limited**.

• Thus, **many theoretical and empirical numerical models** have been proposed for preliminary tornado-resistant design of buildings and structures.

• Objective is to **proposes a new empirical modeling (1st year)** for a tornado vortex and **its effects on low-rise / tall buildings and flying characteristics of wind-borne debris (2nd year)** were investigated and compared with other existing numerical models.

Equations of motion



- Time independent • Axisymmetric
- Pressure = function(r, z)
- No body forces

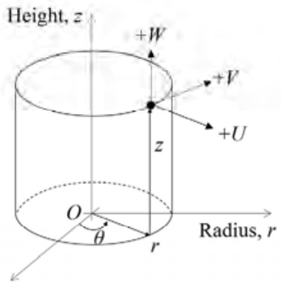
Momentum equation

- Radial $\quad \bar{U}\frac{\partial \bar{U}}{\partial \bar{r}} + \frac{\bar{W}}{\zeta}\frac{\partial \bar{U}}{\partial \bar{z}} - \frac{\bar{V}^2}{\bar{r}} = -\frac{\partial \bar{P}}{\partial \bar{r}}$
- Tangential $\quad \bar{U}\frac{\partial \bar{V}}{\partial \bar{r}} + \frac{\bar{W}}{\zeta}\frac{\partial \bar{V}}{\partial \bar{z}} + \frac{\bar{U}\bar{V}}{\bar{r}} = 0$
- Vertical $\quad \zeta\bar{U}\frac{\partial \bar{W}}{\partial \bar{r}} + \bar{W}\frac{\partial \bar{W}}{\partial \bar{z}} = -\frac{\partial \bar{P}}{\partial \bar{z}}$

Mass conservation equation $\quad \frac{\partial \bar{U}}{\partial \bar{r}} + \frac{1}{\zeta}\frac{\partial \bar{U}}{\partial \bar{z}} + \frac{\bar{U}}{\bar{r}} = 0 \qquad \zeta = \frac{z_{ref}}{r_{ref}}$

where, parameters are normalized by U_{ref}, r_{ref}, z_{ref}, and ρU_{ref}^2

Equations of motion



- Time independent • Axisymmetric
- Pressure = function(r, z)
- No body forces
- **Velocity components = $f(r) \times f(z)$**

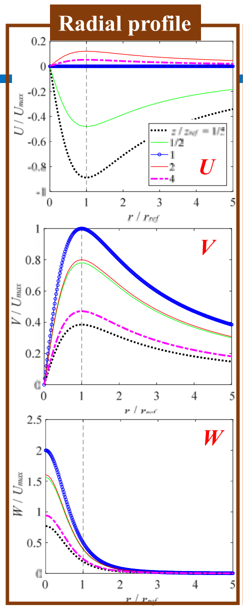
Radial U	$\bar{U} = \frac{-2\bar{r}(1-\bar{z}^2)}{(1+\bar{r}^2)(1+\bar{z}^2)^2}$
Tangential V	$\bar{V} = \frac{4\bar{r}\bar{z}}{(1+\bar{r}^2)(1+\bar{z}^2)}$
Vertical W	$\bar{W} = \frac{4\zeta\bar{z}}{(1+\bar{r}^2)^2(1+\bar{z}^2)}$

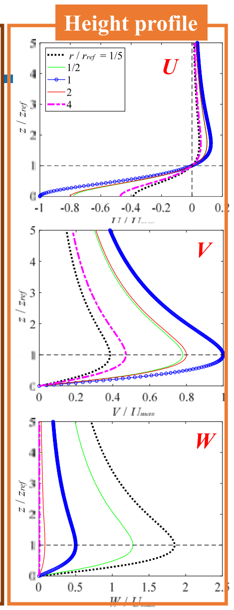
Parameters:
U_{max}, r_{ref}, z_{ref}

$(\zeta = z_{ref} / r_{ref})$

Proposed model: Characteristics

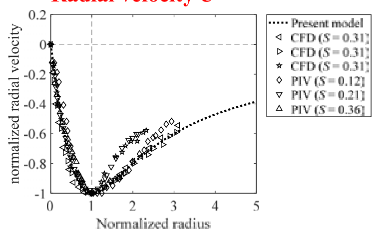
- **Maximum radial velocity was found at the ground**, reflecting the findings of field measurement and experiments, i.e. the strongest inflow was concentrated very near the ground.
- Maximum radial and tangential velocities were shown at $\bar{r}$=1 and maximum tangential and vertical velocities were shown at $\bar{z}$=1.
- The velocity components show **clear variations with radius and height**, overcoming the shortcomings of existing numerical models.

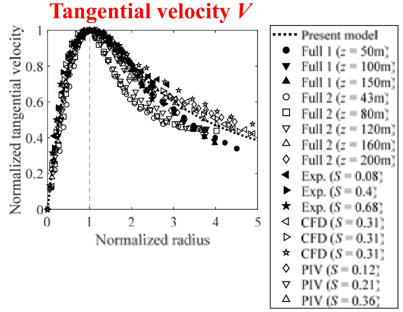


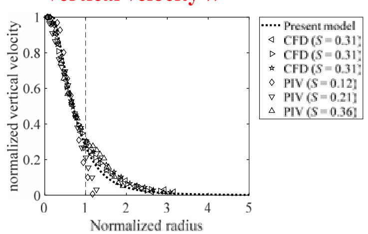


From Kim and Tamura (2021)

Proposed model: Radial variation



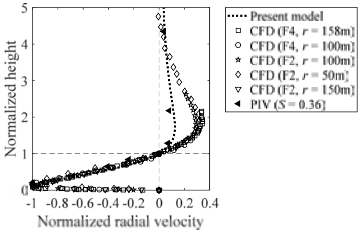




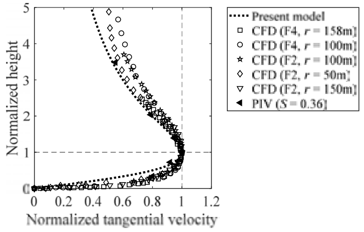
From Kim and Tamura (2021)

Proposed model: Vertical variation

Radial velocity U



Tangential velocity V



The proposed model shown by a dotted line shows **good agreement** with existing data.

From Kim and Tamura (2021)

Other numerical model

Using proposed model, **peak normal stresses** on low-rise building and **aerodynamic force coefficients** on tall building were calculated and compared with those obtained from existing numerical models shown below.

- Modified Rankine model (1882, $\varepsilon = 0.5$)
- Burgers-Rott model (1948, 1958)
- Kuo-Wen model (1971, 1975)
- Fujita model (1978)
- Baker model (2016)

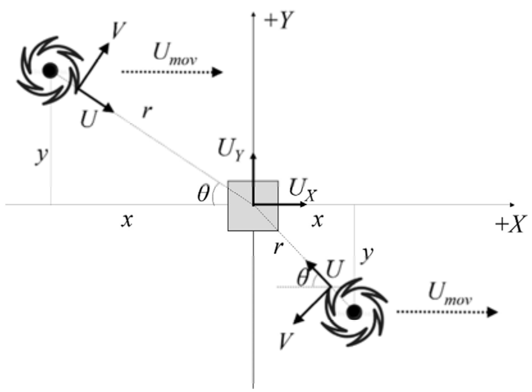
Proposed model

$$\bar{U} = \frac{-2\bar{r}(1-\bar{z}^2)}{(1+\bar{r}^2)(1+\bar{z}^2)^2}$$

$$\bar{V} = \frac{4\bar{r}\bar{z}}{(1+\bar{r}^2)(1+\bar{z}^2)}$$

$$\bar{W} = \frac{4\zeta\bar{z}}{(1+\bar{r}^2)^2(1+\bar{z}^2)}$$

Peak normal stresses on low-rise building



Tornado properties:

$U_{mov} = 15$m/s

$U_{ref} = 65$m/s

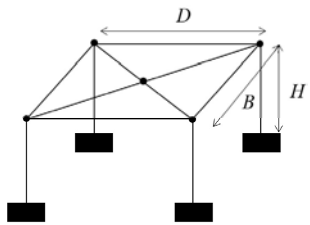
$r_{ref} = 50$m

$z_{ref} = 50$m

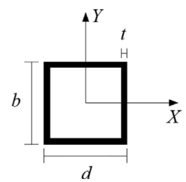
x = -500m ~ 500m (1m interval)

y = -200m ~ 200m (1m interval)

Peak normal stresses on low-rise building



$B \times D \times H = 20\text{m} \times 20\text{m} \times 10\text{m}$



$b = d = 0.5$m

$t = 0.02$m

$A = 0.0384\text{m}^2$

$Z_X = Z_Y = 0.005908\text{m}^3$

$F_i = 0.5\rho U_i^2 C_i A_{ref}$

$C_i = 1.2$, $i = X, Y, Z$

$M_X = (5/16) F_Y H$

$M_Y = (5/16) F_X H$

$(I_{beam} = I_{column})$

$\sigma_X = M_X / Z_X$

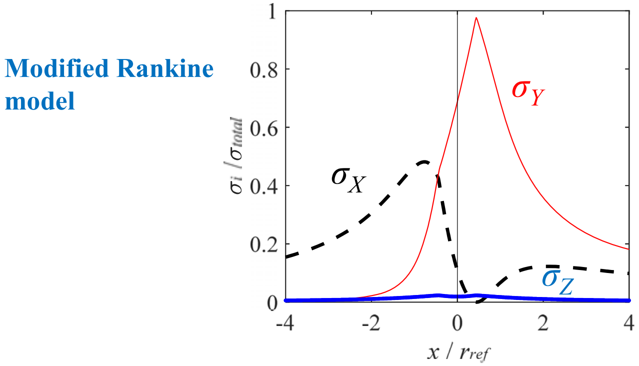
$\sigma_Y = M_Y / Z_Y$

$\sigma_Z = F_Z / A$

$\boldsymbol{\sigma_{total} = \sigma_X + \sigma_Y + \sigma_Z}$

Contribution of each stress component

At a point where the maximum total stress σ_{total} occurs.



$\sigma_X = M_X / Z_X$

$\sigma_Y = M_Y / Z_Y$

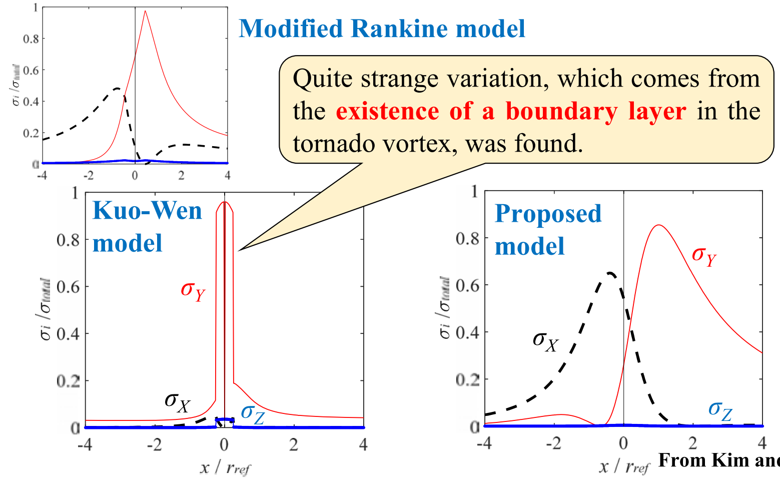
$\sigma_Z = F_Z / A$

σ_Y is the largest and σ_Z is the smallest. σ_Z was resulted only from the vertical velocity, implying that the vertical velocity could be ignored in the calculation of tornado-induced load by the surface pressure.

From Kim and Tamura (2021)

Contribution of each stress component

At a point where the maximum total stress σ_{total} occurs.



From Kim and Tamura (2021)

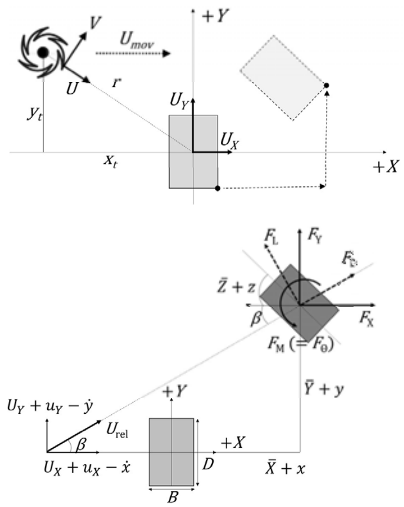
Maximum total stress σ_{total}

Modified Rankine model ($\sigma_{total,Rankine} \approx 61 kN/cm^2$)

The maximum total stress of the modified Rankine model is the largest, and the smallest one is found for the Baker model, which is only 20% of the modified Rankine model. The maximum total stresses of the Burgers-Rott, Kuo-Wen, Fujita and the proposed models show similar value, corresponding to almost 80% of that of the modified Rankine model.

From Kim and Tamura (2021)

Aerodynamic forces on tall building



$B \times D \times H = 30m \times 45m \times 250m$

Tornado properties:

$U_{mov} = 15m/s$

$U_{ref} = 65m/s$

$r_{ref} = 50m$

$z_{ref} = 50m$

A tornado was assumed to **pass through the center of the building** along the X-axis

Aerodynamic forces on tall building

The resulting aerodynamic forces $F_D(h)$ and $F_L(h)$ at elevation h

($C_D = 1.0$, $C_L = -0.1$, $C_D' = -1.1$, $C_L' = 2.2$, $\beta = \tan^{-1}(U_Y/U_X)$)

$$F_D(h) = \frac{1}{2}\rho D\left[C_D\left(U_X(h)^2 + U_Y(h)^2\right) + U_X(h)^2\left\{C_D\left(\frac{2u_X(h)}{U_X(h)}\right) + C_D'\beta\left(1 + \frac{2u_X(h)}{U_X(h)}\right)\right\} + U_Y(h)^2\left\{C_D\left(\frac{2u_Y(h)}{U_Y(h)}\right) + C_D'\beta\left(1 + \frac{2u_Y(h)}{U_Y(h)}\right)\right\}\right]$$

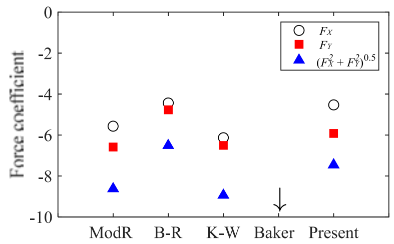
I_X I_Y

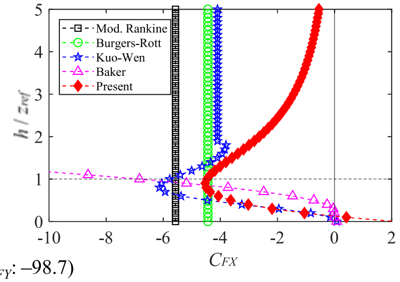
$$F_L(h) = \frac{1}{2}\rho D\left[C_L\left(U_X(h)^2 + U_Y(h)^2\right) + U_X(h)^2\left\{C_L\left(\frac{2u_X(h)}{U_X(h)}\right) + C_L'\beta\left(1 + \frac{2u_X(h)}{U_X(h)}\right)\right\} + U_Y(h)^2\left\{C_L\left(\frac{2u_Y(h)}{U_Y(h)}\right) + C_L'\beta\left(1 + \frac{2u_Y(h)}{U_Y(h)}\right)\right\}\right]$$

Maximum aerodynamic force coefficient

Maximum value **for all heights through out the tornado passage**

→ The heights for the maximum value differs depending on models.



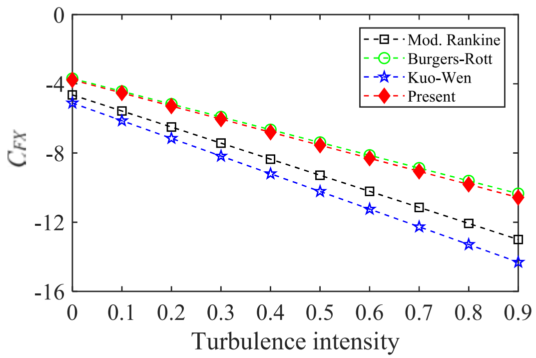


(For the Baker model, C_{FX}: –110.6, C_{FY}: –98.7)

The **modified Rankine** and **Kuo-Wen models** show larger values, and the proposed model shows intermediate value. The **Baker model** shows the largest one, because velocity components increase to infinity with height.

From Kim and Tamura (2021)

Effect of I_X and I_Y



$I_X = I_Y = 0, 0.1, \cdots, 0.9$

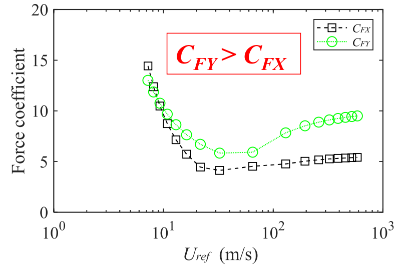
Aerodynamic force coefficients **increase by roughly 10%** when the turbulence intensities increase by 10%.

From Kim and Tamura (2021)

Effect of U_{ref} and U_{mov}

Reference velocity U_{ref}

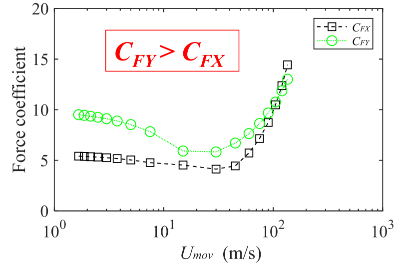
U_{ref} = 7m/s ~ 585m/s



Aerodynamic force coefficients decrease with increasing reference velocity and increase slightly with increasing reference velocity.

Moving velocity U_{mov}

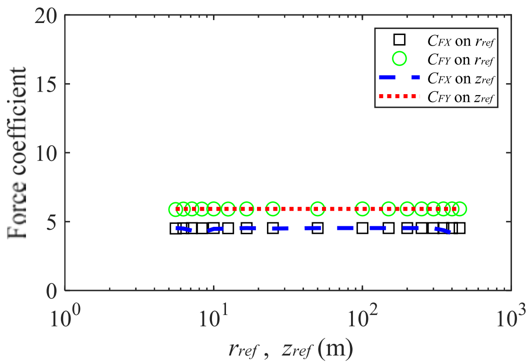
U_{mov} = 1.7m/s ~ 135m/s



Opposite trend to U_{ref}

From Kim and Tamura (2021)

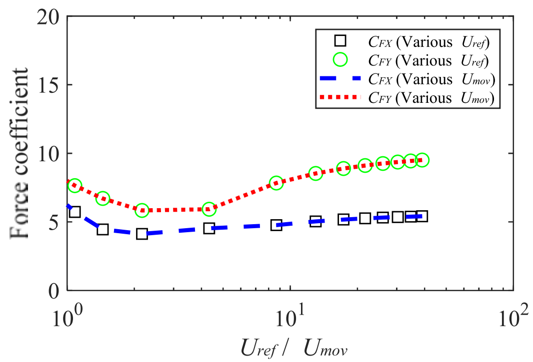
Effect of r_{ref} and z_{ref}



Aerodynamic force coefficients were **little influenced** by the reference radius and reference height.

From Kim and Tamura (2021)

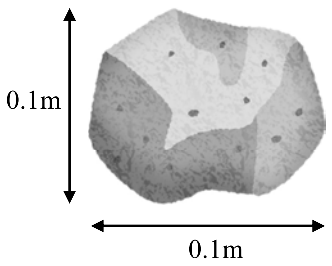
Combined effect of U_{ref} and U_{mov}, U_{ref}/U_{mov}



Aerodynamic force coefficients were **well collapsed for the same normalized velocity** ***U_{ref}/U_{mov}***, implying that the combined effects of reference velocity and moving velocity are **more meaningful** than the individual effects.

From Kim and Tamura (2021)

Characteristics wind-borne debris



Wind-borne debris: Stone or roof tile

Size: 0.1m × 0.1m × 0.1m

Mass m: 3kg

Aerodynamic parameter $C_D A/m$

: 0.01m²/kg

T_a ($\rho U_{ref}^2/2C_D g \cdot C_D A/m$): 1.35

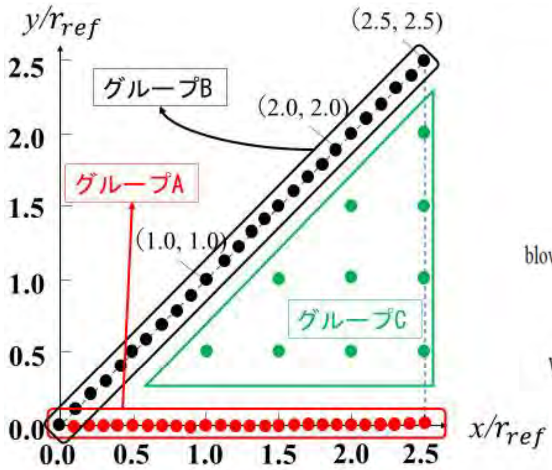
Initial velocity ($\dot{x}, \dot{y}, \dot{z}$): (0, 0, 0)

Tornado properties:

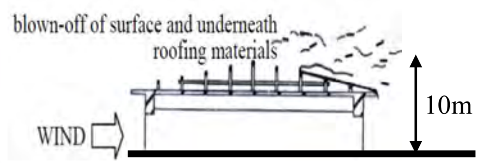
$U_{mov} = 0$, $U_{ref} = 65$m/s

$r_{ref} = 50$m, $z_{ref} = 50$m

Initial positions of wind-borne debris



$(x, y, z) = (x, y, 10\text{m})$



From Uematsu et al., (1992)

Equations of motion of wind-borne debris

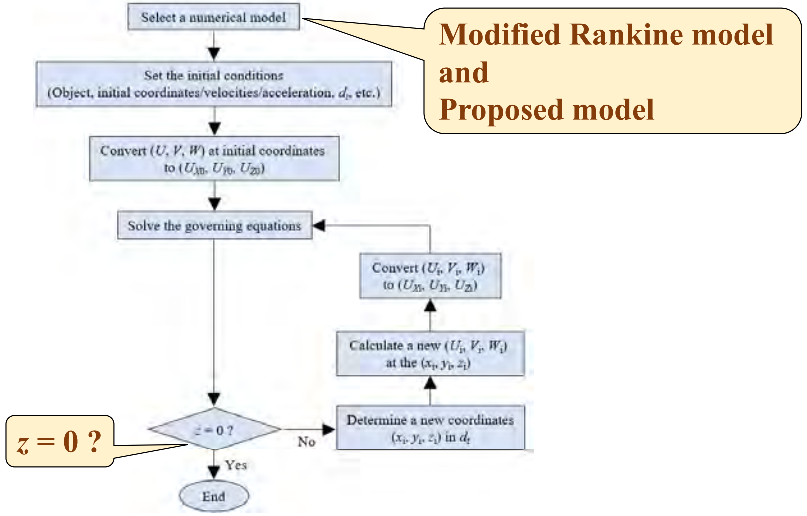
X-direction: $$\frac{d\dot{x}}{dt} = \frac{\rho A C_D}{2m}(U_X - \dot{x})\sqrt{(U_X - \dot{x})^2 + (U_Y - \dot{y})^2 + (U_Z - \dot{z})^2}$$

Y-direction: $$\frac{d\dot{y}}{dt} = \frac{\rho A C_D}{2m}(U_Y - \dot{y})\sqrt{(U_X - \dot{x})^2 + (U_Y - \dot{y})^2 + (U_Z - \dot{z})^2}$$

Z-direction: $$\frac{d\dot{z}}{dt} = \frac{\rho A C_D}{2m}(U_Z - \dot{z})\sqrt{(U_X - \dot{x})^2 + (U_Y - \dot{y})^2 + (U_Z - \dot{z})^2} - g$$

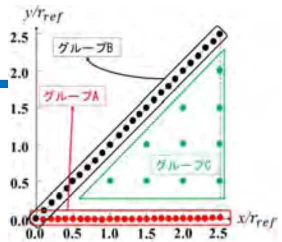
Impact load: $$W_M = \frac{m\{(\dot{x}^2 + \dot{y}^2)^{0.5}\}^2}{L_{min}}$$ (Riera Equation)

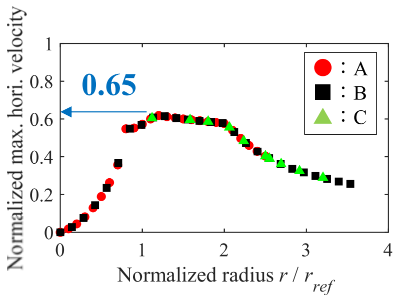
Flowchart of calculation



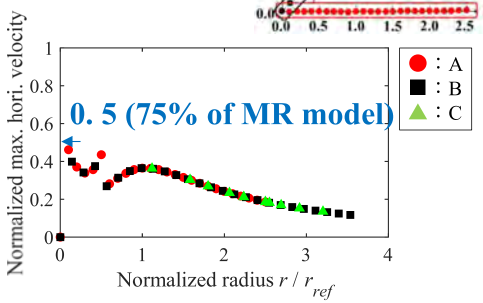
Maximum horizontal velocity of wind-borne debris

$(\dot{x}^2 + \dot{y}^2)^{0.5}/U_{ref}$



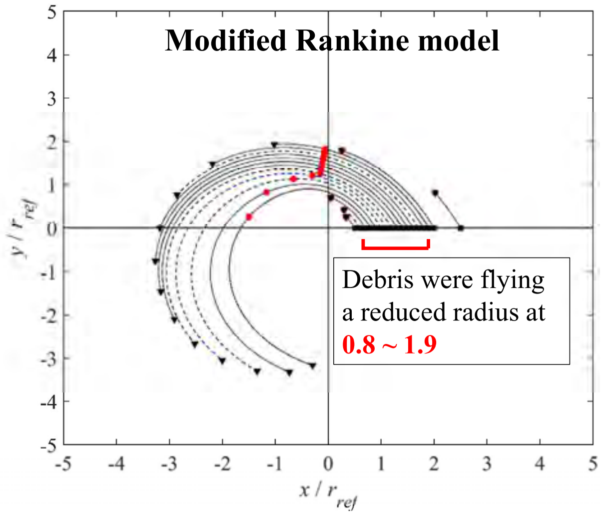


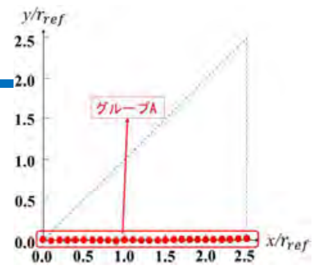
Modified Rankine model



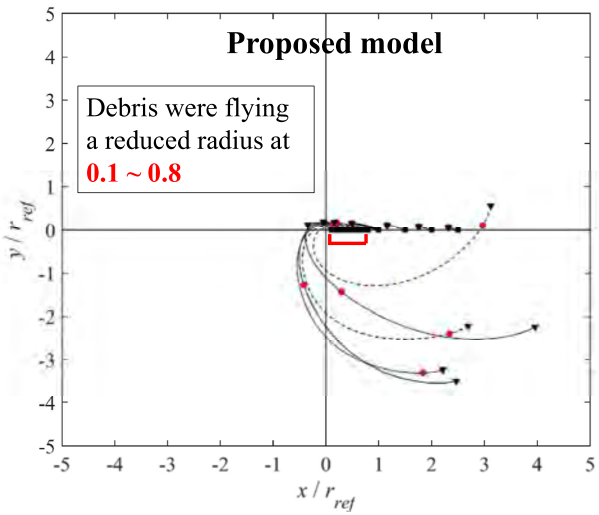
Proposed model

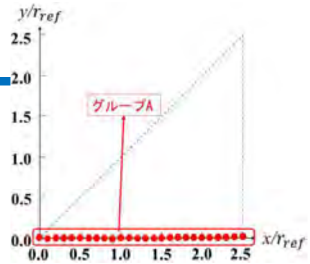
Flying trajectory in X-Y plane





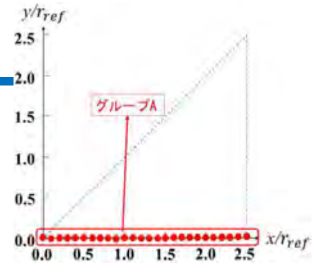
Flying trajectory in *X-Y* plane



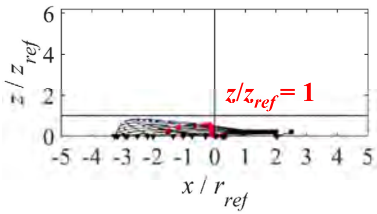


▼: $z = 0$
●: Location where the maximum horizontal velocity occurs

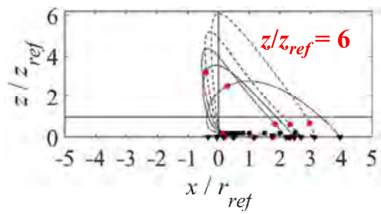
Flying trajectory in *X-Z* plane



▼: $z = 0$
●: Location where the maximum horizontal velocity occurs



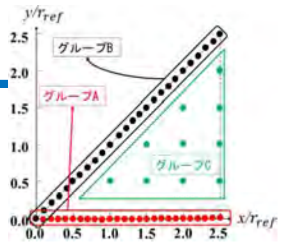
Modified Rankine model

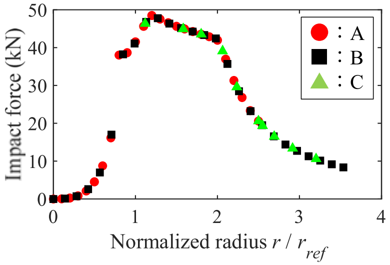


Proposed model

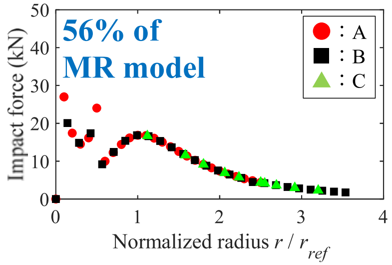
Comparison of impact loads

$$W_M = \frac{m\{(\dot{x}^2 + \dot{y}^2)^{0.5}\}^2}{L_{min}} \quad \text{(Riera Equation)}$$





Modified Rankine model



Proposed model

$U_{add,MRM} \approx$ **21m/s**
$U_{add,PM} \approx$ **16m/s**
when,
$\rho = 1.25 kg/m^3$
$A = 10m \times 15m$
$C_D = 1.2$

Concluding remarks (1/2)

- A **new empirical model** for tornado vortex was proposed, and **peak normal stresses** on low-rise building, **aerodynamic forces** on tall buildings, **flying characteristics** of wind-borne debris were calculated and compared with those from several existing models.

- There are **three parameters in the proposed model**, and the velocity components show **clear variations with radius and height**, overcoming the shortcomings of existing numerical models.

- In the proposed model, **the maximum radial flow was found at the ground**, reflecting the results of field measurement and wind tunnel experiment, i.e. the strongest inflow was concentrated very near the ground.

Concluding remarks (2/2)

• The maximum total stress on column on low-rise building **the modified Rankine model was the largest**, and **that of the proposed model show similar value to other numerical models**.

• Aerodynamic force coefficients on tall building were calculated based on the simplified quasi-steady theory. **The results from the proposed model show similar values to most existing models**, while those from the Baker model show much larger values. Aerodynamic force coefficients **collapsed to one curve for the same U_{ref}/U_{mov}**. The effects of reference radius and reference height were found to be small.

• **Maximum horizontal velocity** from the proposed model was about **75%** of that of the modified Rankine model, giving **maximum impact loads about 56%** of that of the modified Rankine model.

Thank you very much

ACCOMPLISHMENTS

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