Development of snow accretion simulation method for electric wires in consideration of snow melting and shedding

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Objectives

(1) CRIEPI have developed SNOVAL(Ver.2) (Snow accretion simulation code for overhead transmission lines) which can simulate the temporal change of three dimensional accreted snow shape under calm to strong wind in any direction, without solving air flow around snow deposit and trajectories of snowflakes before impact. SNOVAL(Ver.2) can estimate the mass of accreted snow with arbitrary shape and electric wire rotation, in contrast to the existing cylindrical-sleeve accretion models.

(2) SNOVAL(Ver.2) has been improved to estimate:

- liquid water content (LWC) by considering melting process due to heat exchanges between the air, electric wire and snow deposit and melting of snowflakes below freezing level in the atmosphere,
- density of accreted snow as a function of wind speed and LWC of snow deposit,
- accretion factor as a function of wind speed, LWC of snowflakes before impact and three dimensional snow accretion shape,
- snow shedding based on the balance of forces and its related moments exerted on accreted snow with different shapes.

Reproduce the process from the start of snow accretion until snow shedding.
Snow accretion growth

Smooth cylindrical electric wire

Large inertia of snowflakes

Impinging snow flux $S$

Density of water $\rho_w$

Precipitation rate $[\text{mm/10min}]$

Wind speed $v_f$

Wind direction

Final falling speed of snowflakes $v_f$

Azimuth

Thickness of accreted snow $h(x, \psi, t)$

Accretion factor

$$\frac{\partial h}{\partial t} = \frac{\sigma(t)(-S \cdot n_e)}{\rho_s(t)(N \cdot n_e)}$$

Density of accreted snow $\sigma(t)$

Mass of accreted snow $m[\text{kg/m}]$

$$m(t) = \frac{\rho_s(t)}{2L_x} \int_0^{\frac{\pi}{2}} \int_0^{\frac{\pi}{2}} ((R + h)^2 - R^2) d\psi dx$$

Length of electric wire $L_x$

Applicable under calm to strong wind in any direction

Electric wire

Snow deposit

Impinging snow flux $S$

Precipitation rate $[\text{mm/10min}]$

Wind speed $v_f$

Wind direction

Final falling speed of snowflakes $v_f$

Azimuth
Electric wire rotation

Equation for electric wire rotation angle $\varphi$

$$I \frac{\partial^2 \varphi(x, t)}{\partial t^2} = GJ \frac{\partial^2 \varphi(x, t)}{\partial x^2} + M'_s(x, t) + M'_w(x, t)$$

Torsional stiffness [Nm$^2$]

Moments due to gravitational and aerodynamic forces [Nm/m]

Gravitational force

Aerodynamic force (only drag force)

Moments due to gravitational and aerodynamic forces [Nm/m]

Nonlinear eq with respect to $\varphi$

Spatial discretization

Galerkin finite element method

Time integration

Crank-Nicolson method

Iteration

Newton-Raphson method

Electric wire rotation

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Melting of snow deposit and LWC

Heat exchanges between air, electric wire and snow deposit

Mass of melt water: \( m_w \) [kg/m]

\[
\frac{dm_w}{dt} = \left( Q_c(t) + Q_e(t) + Q_{AI}(t) \right)/L_f
\]

Convection

Evaporation/Condensation

Conduction across electric wire

Latent heat of fusion

Liquid water content of snowflakes before impact \( \lambda \)

Matsuo & Sasyo theory for melting of snowflakes below freezing level in the atmosphere

Vertical distribution of air temperature based on MANAL data

Liquid water content (LWC) of snow deposit

total mass of water of snowflakes before impact

\[
\Lambda(t) = \int_0^t \lambda(t)dm(t) + m_w(t)
\]

mass of melt water

mass of snow deposit

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Density of accreted snow

Density vs. wind speed (Sato2014)

Density vs. LWC of snow sample (Hefny2009)

Linear dependence of density on wind speed

\( \rho_s(t) = 300 + 20|v_y| \)

Admirat & Sakamoto (1988)

LWC increases with increasing temperature, relative humidity, falling snowflakes speed, and decreases with increasing precipitation rate and wind speed.

LWC is very sensitive to temperature variation.

\[
\rho_s(t) = \frac{\rho_0 + \frac{550c}{550 - \rho_0}|v_y|}{1 + \frac{c}{550 - \rho_0}|v_y|} \times \left(1 + \Lambda(t) + \Lambda^2(t) + \ldots\right)
\]

\[
\rho_0 + \frac{550c}{550 - \rho_0}|v_y| = \frac{1}{1 + \frac{c}{550 - \rho_0}|v_y|} \times \frac{1}{1 - \Lambda(t)}
\]

\[
c = -\rho_0/25 + 35
\]
Accretion factor

\[ \cos \theta = \frac{(-S \cdot n_c)}{|S|} \]

\[ \sigma(t) = \frac{1 + \cos\{10.5(\lambda(t) - 0.1)\}}{2\sqrt{1 + \left(\frac{|v_y|}{v_f}\right)^2}} A \times (\cos \theta)^\alpha \]

LWC of snowflakes before impact

Accretion factor is highest at a LWC of incoming snowflakes corresponding to the stickiest snow

\[ \sigma = 0 \left( |v_y| > 3 \text{[m/s]} \right) \]

\[ \alpha = B \left| v_y \right|^{1.5} D_s^{0.5} \]

Dry snow

\[ \sigma = 38.0 \]

\[ A = 0.38 \text{ (calibration)} \]

\[ A = 0.40 \text{ Cylindrical-sleeve accretion model (Nygaard, 2013)} \]

\[ \alpha = 0.1 \]

\[ \alpha = 1.0 \]

\[ \alpha = 2.0 \]

Bluff shape  \[ \leftrightarrow \] Streamline shape

\[ \alpha = 0.1 \]

\[ \alpha = 1.0 \]

\[ \alpha = 2.0 \]

\[ D_s \]

\[ v_f \]

\[ |v_y| \]

\[ B = 0.15 \text{ (calibration)} \]
Adhesive strength of wet snow

Measurement on tensile strength

Mizuno & Wakahama (1977)
Hefny et al. (2009)

Adhesive strength of wet snow depends on initially applied compressive stress, LWC, density, surface roughness of materials.

Negative pressure due to capillarity

\[ P_c = -\frac{\gamma_w}{r_c} \]

for \( r_c = 300 \text{~} 500[\mu\text{m}] \)

Adhesive force

LWC of snow sample

Tensile adhesive strength \( \sigma_{tad} \) [N/m²]

\[
\sigma_{tad}(t) = \begin{cases} 
(10.0(\sigma_{tad})_{\text{max}} - 278.0)\Lambda(t) + 27.8 & (0 \leq \Lambda(t) < 0.1) \\
-90.0\Lambda(t) + (\sigma_{tad})_{\text{max}} + 9.0 & (0.1 \leq \Lambda(t) < 0.3) \\
-1045.5\Lambda(t) + (\sigma_{tad})_{\text{max}} + 295.5 & (0.3 \leq \Lambda(t) < 0.4) \\
0 & (0.4 \leq \Lambda(t) \leq 1.0) 
\end{cases}
\]

Shear adhesive strength \( \sigma_{sad} \) [N/m²]

\[
(\sigma_{tad})_{\text{max}} / 2 \leq (\sigma_{sad})_{\text{max}} < (\sigma_{tad})_{\text{max}}
\]

Tensile strength does not exceed twice shear strength for most other materials.
Wet snow shedding

Criterion 1: Gravitational force exceeds tensile adhesive force

\[ f_g(t) > f_{tad}(t) \]

Gravitational force \([\text{N/m}]\)

\[ f_g(t) = m_s(t)g \]

Tensile adhesive force \([\text{N/m}]\)

\[ f_{tad}(t) = \int_{\pi/2}^{\psi_0} \sigma_{tad}(t) \cos(\pi - \psi) Rd\psi \]

\[ = \sigma_{tad}(t) \times 2R(\psi_0 = 3\pi/2) \]

Criterion 2: Moment due to gravity and wind force exceeds moment due to shear adhesive force

\[ M_g(t) + M_w(t) > M_{sad}(t) \]

Moment due to gravity \([\text{Nm/m}]\)

\[ M_g(t) = f_g(t)r_{cg}(t)\sin\theta_{cg}(t) \]

Wind force \([\text{N/m}]\)

\[ f_w(t) = \frac{1}{2} \rho_a |v_y(t)|^2 C_d D_s(t) \]

Drag coefficient

Moment due to wind force \([\text{Nm/m}]\)

\[ M_w(t) = -f_w(t)r_{cg}(t)\cos\theta_{cg}(t) \]

Moment due to shear adhesive force \([\text{Nm/m}]\)

\[ M_{sad}(t) = R \int_{\psi_1}^{\psi_2} \sigma_{sad}(t) Rd\phi \]

The time of wet snow shedding is numerically determined from the point where either criterion 1 or criterion 2 is satisfied.
Conductor samplers supported by wires

Acquisition of meteorological data of wet snow event and snow accretion data on conductor samplers with different size, torsional stiffness, and orientation

Torsion of conductor sampler equivalent to that in the middle of the span of actual transmission line

Observational location

Kushiro

ACSR810mm²
12
11
10
9

ACSR410mm²

ACSR240mm²
8
7
6
5

Snow Resistant Ring

Wire

Load cell

Conductor

Wire

Web camera

ENE wind

NNE wind

CRIEPI

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Wet snow event and analytical condition

Meteorological data at Kushiro in Japan on April 21, 2013

Conductor sampler spec and analytical condition

<table>
<thead>
<tr>
<th></th>
<th>Sampler1</th>
<th>Sampler2</th>
</tr>
</thead>
<tbody>
<tr>
<td>type</td>
<td>ACSR240mm²</td>
<td>ACSR810mm²</td>
</tr>
<tr>
<td>Sampler length Lx</td>
<td>2[m]</td>
<td></td>
</tr>
<tr>
<td>Sampler diameter</td>
<td>0.0224[m]</td>
<td>0.0384[m]</td>
</tr>
<tr>
<td>Torsional stiffness GJ</td>
<td>68.8[Nm²/rad]</td>
<td>588[Nm²/rad]</td>
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<tr>
<td>Equivalent span length 2L</td>
<td>90[m]</td>
<td>300[m]</td>
</tr>
<tr>
<td>Torsional spring constant</td>
<td>0.0680[Nm/rad]</td>
<td>0.0523[Nm/rad]</td>
</tr>
<tr>
<td>Azimuth</td>
<td></td>
<td>π/8</td>
</tr>
<tr>
<td>Drag coefficient C_d</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Space division</td>
<td>Axial direction:10</td>
<td>Circumferential direction: 720</td>
</tr>
<tr>
<td>Time division</td>
<td>1[s]</td>
<td></td>
</tr>
<tr>
<td>Time step</td>
<td>36000</td>
<td></td>
</tr>
<tr>
<td>height of atmosphere</td>
<td>250[m]</td>
<td></td>
</tr>
<tr>
<td>Initial radius of snowflake</td>
<td>0.005[m]</td>
<td></td>
</tr>
<tr>
<td>Parameter in snow density</td>
<td>ρ₀ = 500[kg/m³]</td>
<td></td>
</tr>
<tr>
<td>Maximum of tensile adhesive strength</td>
<td>σ_rad = 300, 360[N/m²]</td>
<td></td>
</tr>
<tr>
<td>Maximum of shear adhesive strength</td>
<td>σ Sad = 150, 220[N/m²]</td>
<td></td>
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</tbody>
</table>

Torsional spring constant

\[ k_s = \frac{4GJ \times L_x}{L^2} \]
Accretion on sampler1 (development on windward side)

<table>
<thead>
<tr>
<th>Observation</th>
<th>Simulation</th>
</tr>
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<tbody>
<tr>
<td>16:00</td>
<td><img src="image1" alt="Image" /> <img src="image2" alt="Image" /></td>
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<td>17:00</td>
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<tr>
<td>18:00</td>
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<tr>
<td>19:00</td>
<td><img src="image7" alt="Image" /> <img src="image8" alt="Image" /></td>
</tr>
<tr>
<td>20:00</td>
<td><img src="image9" alt="Image" /> <img src="image10" alt="Image" /></td>
</tr>
</tbody>
</table>

(1) Although the precipitation is observed from 14:50, snow accretion does not occur until 15:40 because LWC of snow deposit is over 0.4 and hence adhesive force is zero. SNOVAL ver.3 can predict the start time of snow accretion.

(2) Snow shedding starts at 20:30 and mass of accreted snow gradually decreases due to partial shedding. Snow shedding model in SNOVAL ver.3 is based on shedding all at once and hence cannot treat partial shedding.
Accretion on sampler2 (close to cylindrical-sleeve shape)

LWC of snowflakes and snow deposit is very sensitive to temperature variation. Density is mainly correlated with LWC.

\[ f_g(t) > f_{\text{tad}}(t) \]

rotation of 180[deg]

start

snow shedding
Conclusion and future works

(1) SNOVAL(Ver.3) reproduced the start time of snow accretion and the temporal change of mass and shape of accreted snow, electric wire rotation consistent with field observations for conductor samplers. An calibration method was employed to find appropriate values of parameters in accretion factor allowing for the best agreement between calculated and observed mass of snow deposit in some Japanese wet snow events.

(2) The time of snow shedding strongly depends on the tensile and shear adhesive strength. It is necessary to estimate these strength experimentally for various LWC and density of snow deposit, different surface roughness of materials and initial compressive stress.

(3) Employing many wet snow events, the versatility of proposed accretion factor and density must be enhanced to improve the accuracy in the estimation of accreted snow load currently used.

(4) Effects of solar radiation and heat generated by electric current on LWC of snow deposit and snow shedding must be incorporated in SNOVAL(Ver.3).