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

Civil Engineering Research Laboratory
Central Research Institute of Electric Power Industry

K. Ueno, Y. Eguchi, T. Nishihara, S. Sugimoto, H.Matsumiya

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CRIEPI
Central Research Institute of Electric Power Industry

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.

snow cap　　axial growth　　cylindrical growth

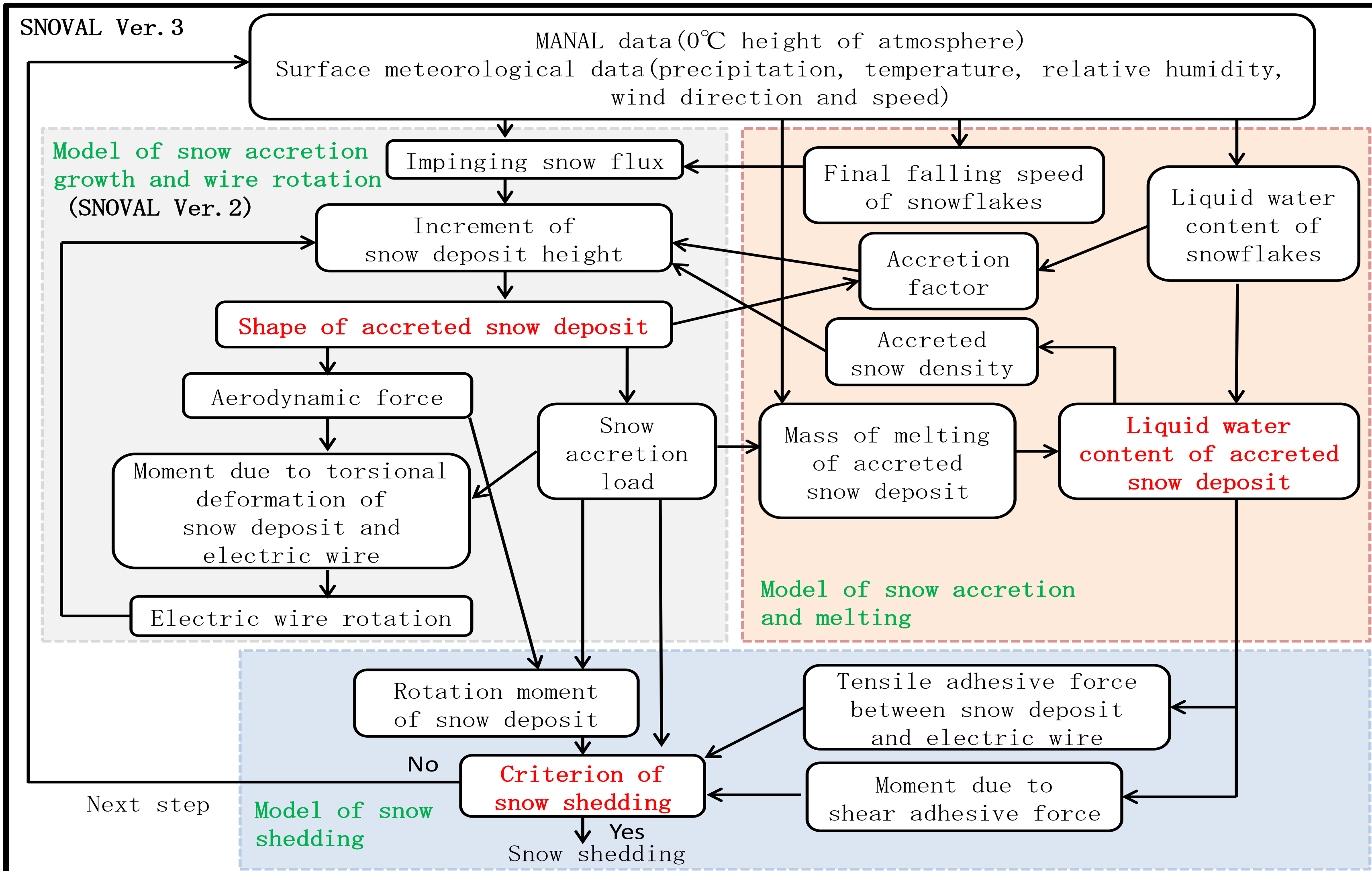
(2) SNOVAL(Ver.2) has been improved to estimate:

- 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.

→ SNOVAL (Ver.3)

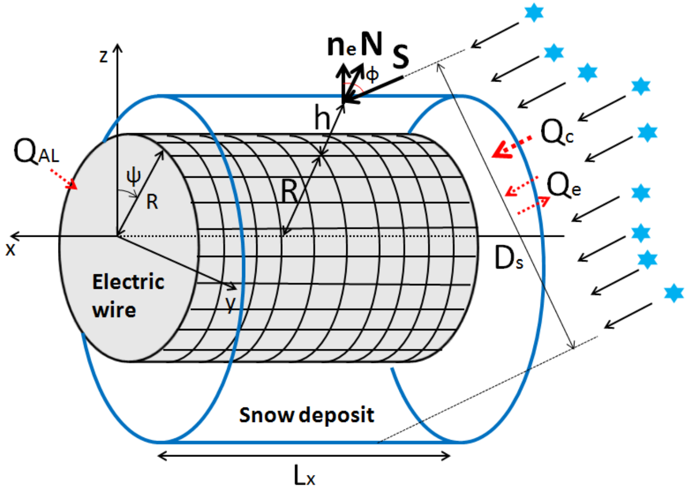
→ Reproduce the process from the start of snow accretion until snow shedding

Framework of SNOVAL(Ver.3)



Snow accretion growth

Smooth cylindrical electric wire



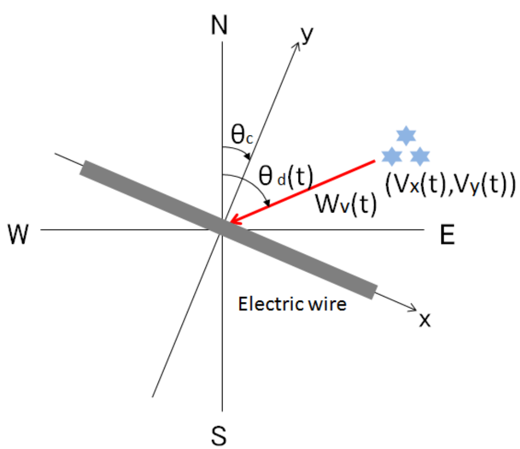
Large inertia of snowflakes

Impinging snow flux **S**

Density of water — Precipitation rate [mm/10min] — Wind speed — Wind direction

$$\mathbf{S}(t)=\begin{pmatrix} S_x(t)\\ S_y(t)\\ S_z(t)\end{pmatrix}=\frac{\rho_w P(t)\times 10^{-3}}{600 v_f}\begin{pmatrix} -w_v(t)\sin(\theta_d(t)-\theta_c)\\ -w_v(t)\cos(\theta_d(t)-\theta_c)\\ -v_f\end{pmatrix}$$

Final falling speed of snowflakes — Azimuth



Thickness of accreted snow

$$h(x,\psi,t)$$

Accretion factor

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

Density of accreted snow

Mass of accreted snow m[kg/m]

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

Length of electric wire

Applicable under calm to strong wind in any direction

Electric wire rotation

Equation for electric wire rotation angle φ

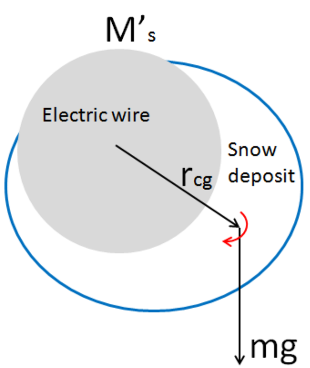
Torsional stiffness[Nm²]

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

Moment of inertia

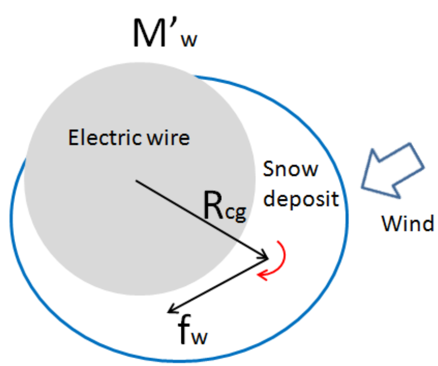
Moments due to gravitational and aerodynamic forces[Nm/m]

Nonlinear eq with respect to φ



Gravitational force

Eccentric load



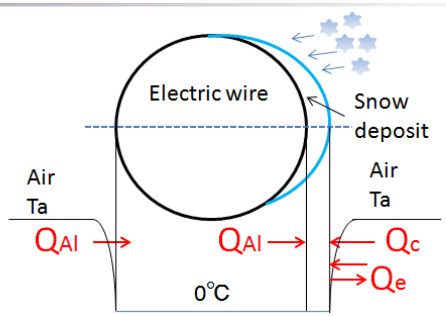
Aerodynamic force
(only drag force)

Spatial discretization	Galerkin finite element method
Time integration	Crank-Nicolson method
Iteration	Newton-Raphson method

Electric wire rotation

Melting of snow deposit and LWC

Heat exchanges between air, electric wire and snow deposit



Mass of melt water : m_w[kg/m]

Convection
Evaporation/Condensation

$$\frac{dm_w}{dt} = \left(Q_c(t) + Q_e(t) + Q_{Al}(t)\right)/L_f$$

Conduction across electric wire

Latent heat of fusion

Liquid water content of snowflakes before impact λ

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

Liquid water content (LWC) of snow deposit

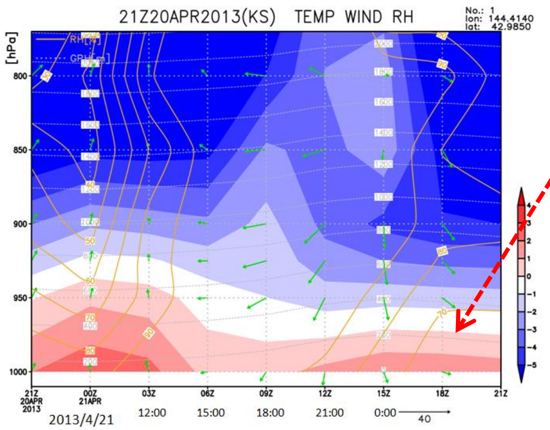
total mass of water of snowflakes before impact

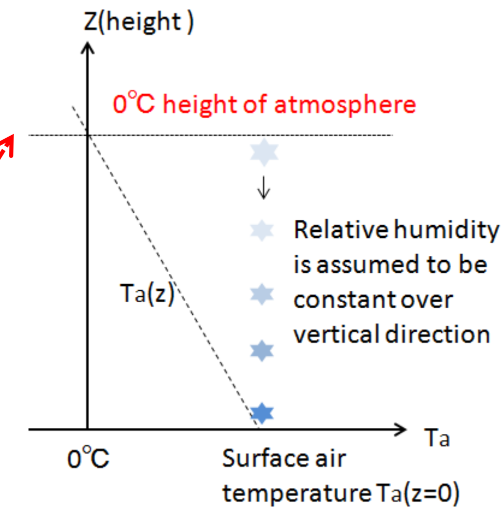
mass of melt water

$$\Lambda(t) = \frac{\int_0^t \lambda(t)dm(t) + m_w(t)}{m(t)}$$

mass of snow deposit

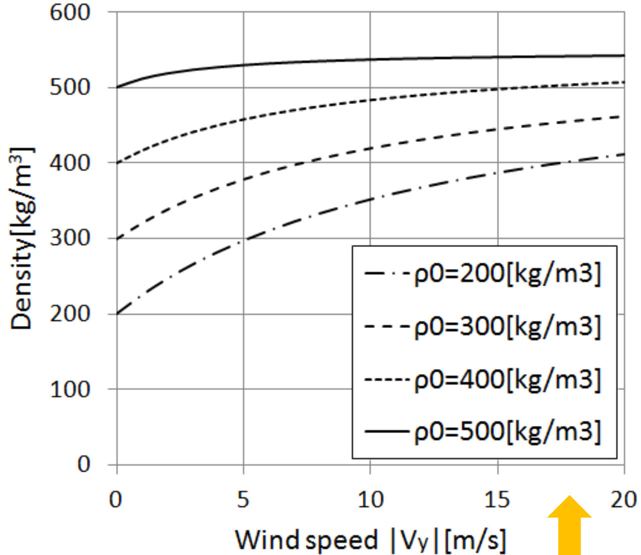
Vertical distribution of air temperature based on MANAL data



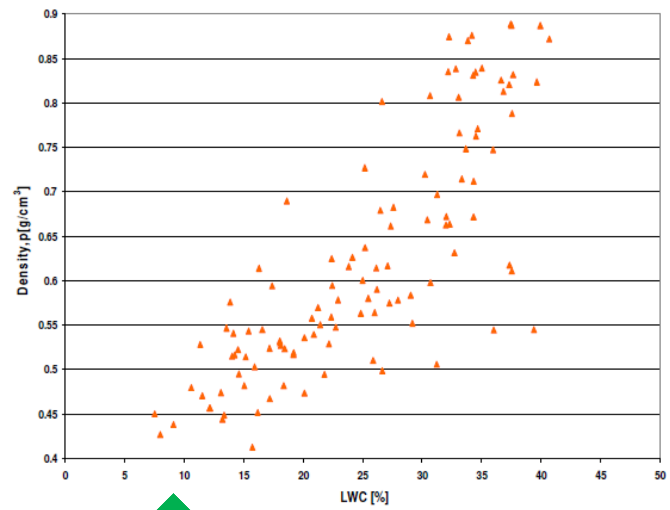


Density of accreted snow

Density vs. wind speed (Sato2014)



Density vs. LWC of snow sample（Hefny2009）



Linear dependence of density on wind speed

$$\rho_s(t) = 300 + 20\left|v_y\right|$$

Admirat & Sakamoto (1988)

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

LWC

$$= \frac{\rho_0 + \frac{550c}{550-\rho_0}\left|v_y\right|}{1+\frac{c}{550-\rho_0}\left|v_y\right|} \times \frac{1}{1-\Lambda(t)}$$

$$c = -\rho_0/25 + 35$$

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.

Accretion factor

$$\cos\theta = \frac{(-\mathbf{S}\cdot\mathbf{n}_e)}{|\mathbf{S}|}$$

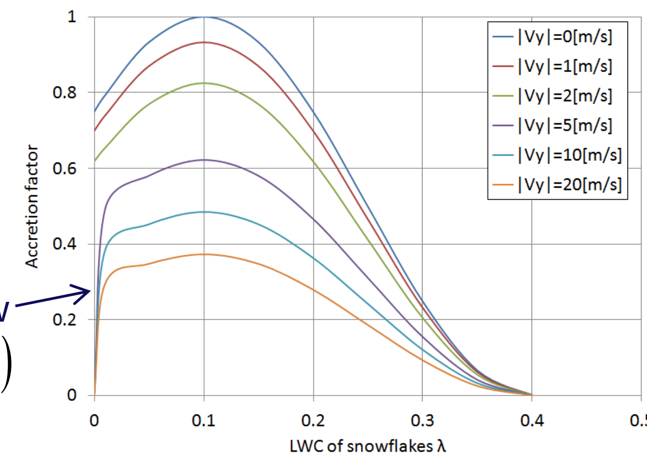
LWC of snowflakes before impact

$$\sigma(t) = \frac{1+\cos\{10.5(\lambda(t)-0.1)\}}{2\sqrt{1+(|v_y|/v_f)^2}^{\,A}} \times (\cos\theta)^{\alpha}$$

$A = 0.38$ (calibration)

$A = 0.40$ Cylindrical-sleeve accretion model (Nygaard, 2013)

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

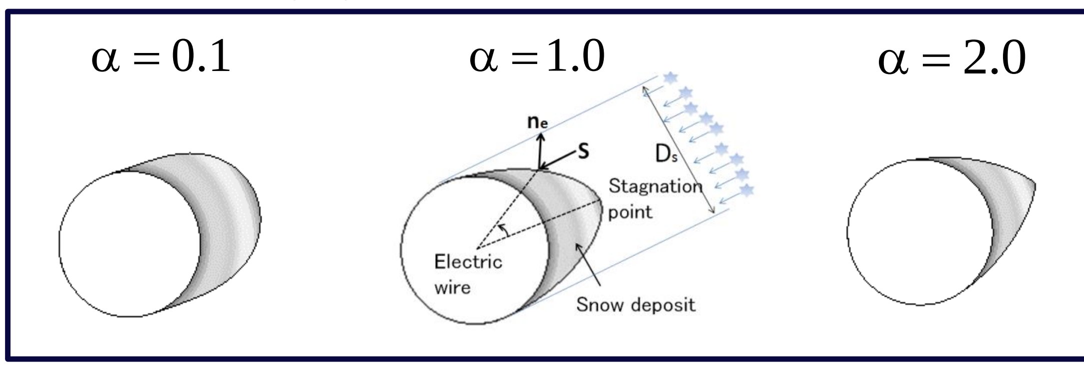


Dry snow

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

(∝wind shear force)

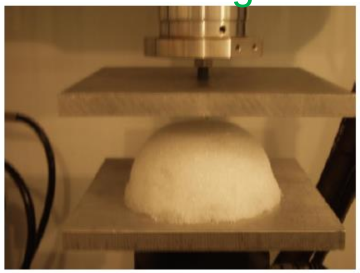
$\alpha = B|v_y|^{1.5} D_s^{0.5}$ $B = 0.15$ (calibration)



Bluff shape ⟷ Streamline shape

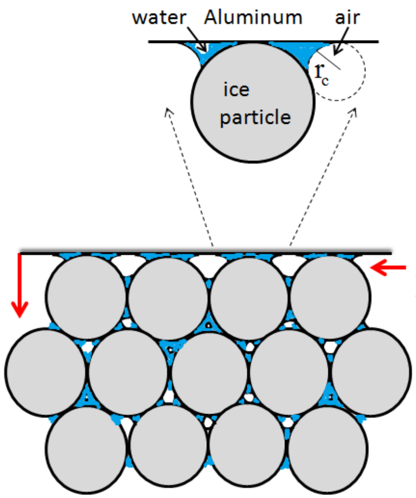
Adhesive strength of wet snow

Measurement on tensile strength



Mizuno & Wakahama (1977)

Hefny et al. (2009)



Negative pressure due to capillarity

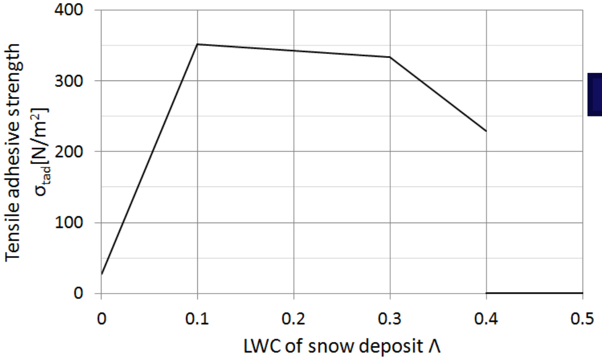
surface tension of water

$$P_c = -\gamma_w / r_c = -(140 \sim 240)[N/m^2]$$

for $r_c = 300 \sim 500[\mu m]$

Adhesive force

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



Sato(1974)

Tensile adhesive strength σ_{tad} [N/m²]

LWC of snow sample

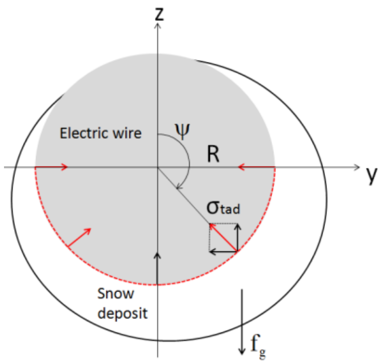
$$\sigma_{tad}(t) = \begin{cases} (10.0(\sigma_{tad})_{max} - 278.0)\Lambda(t) + 27.8 \; (0 \le \Lambda(t) < 0.1) \\ -90.0\Lambda(t) + (\sigma_{tad})_{max} + 9.0 \; (0.1 \le \Lambda(t) < 0.3) \\ -1045.5\Lambda(t) + (\sigma_{tad})_{max} + 295.5 \; (0.3 \le \Lambda(t) < 0.4) \\ 0 \; (0.4 \le \Lambda(t) \le 1.0) \end{cases}$$

Shear adhesive strength σ_{sad} [N/m²]

$$(\sigma_{tad})_{max} / 2 \le (\sigma_{sad})_{max} < (\sigma_{tad})_{max}$$

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

Wet snow shedding



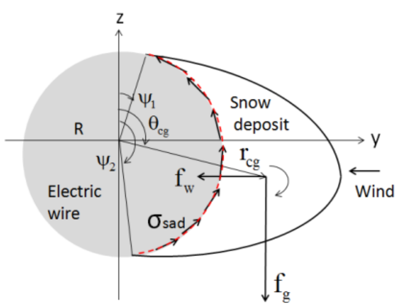
Gravitational force[N/m] $f_g(t) = m_s(t)g$

Tensile adhesive force[N/m]

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

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

Criterion1: Gravitational force exceeds tensile adhesive force $f_g(t) > f_{tad}(t)$



Moment due to gravity[Nm/m] $M_g(t) = f_g(t)r_{cg}(t)\sin\theta_{cg}(t)$

Wind force[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[Nm/m] $M_w(t) = -f_w(t)r_{cg}(t)\cos\theta_{cg}(t)$

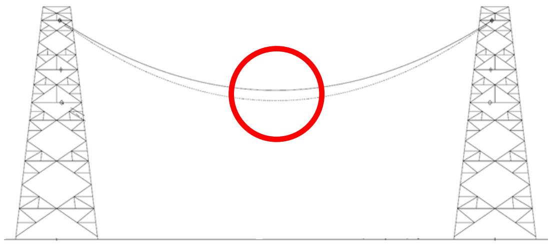
Moment due to shear adhesive force[Nm/m] $M_{sad}(t) = R\int_{\psi_1}^{\psi_2} \sigma_{sad}(t)Rd\phi$

Criterion 2: Moment due to gravity and wind force exceeds moment due to shear adhesive force $M_g(t) + M_w(t) > M_{sad}(t)$

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

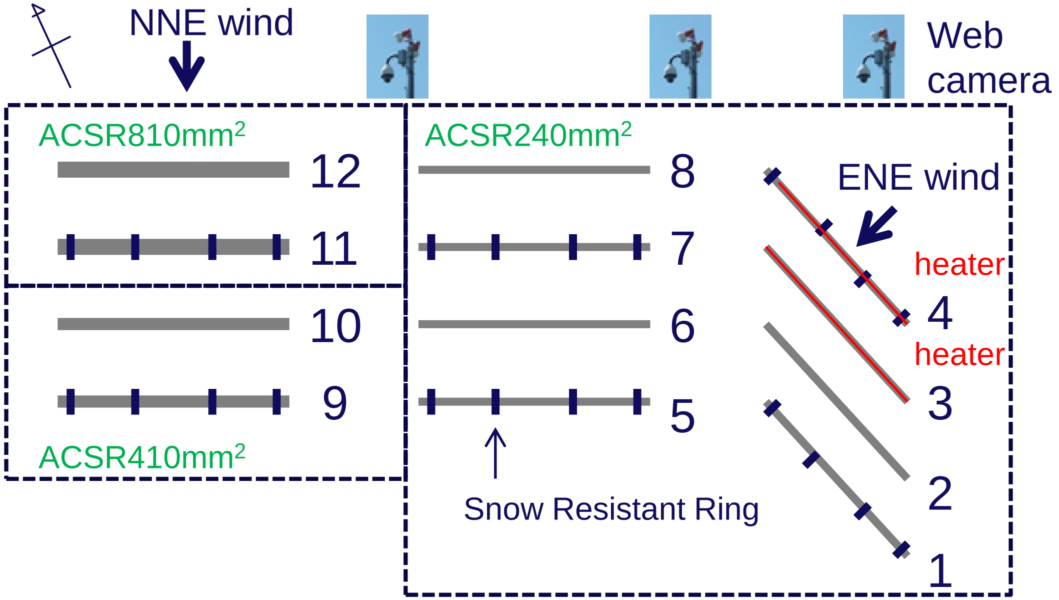
Conductor samplers supported by wires

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



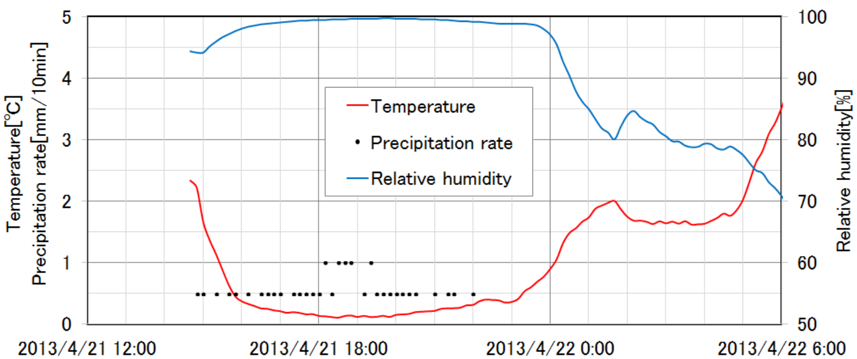
Torsion of conductor sampler equivalent to that in the middle of the span of actual transmission line

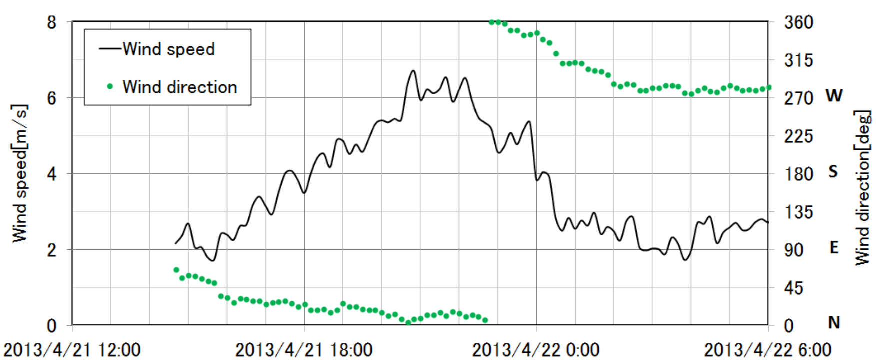
Observational location



Wet snow event and analytical condition

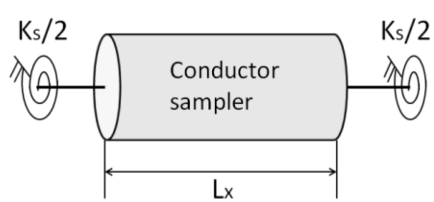
Meteorological data at Kushiro in Japan on April 21, 2013





Torsional spring constant

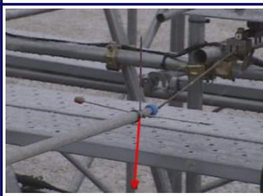
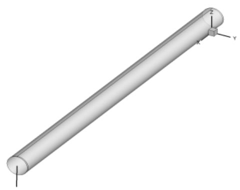
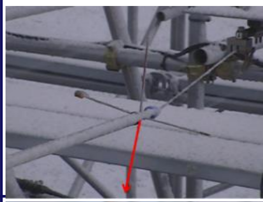
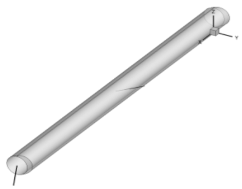
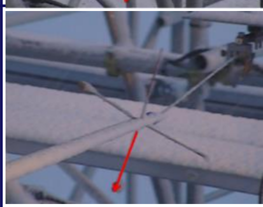
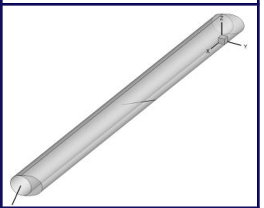
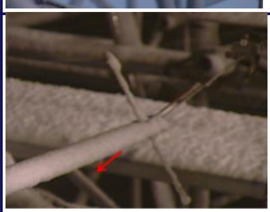
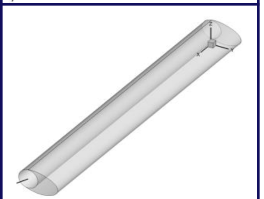
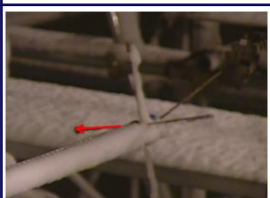
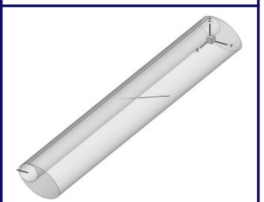
$$k_s = 4GJ \times L_x / L^2$$

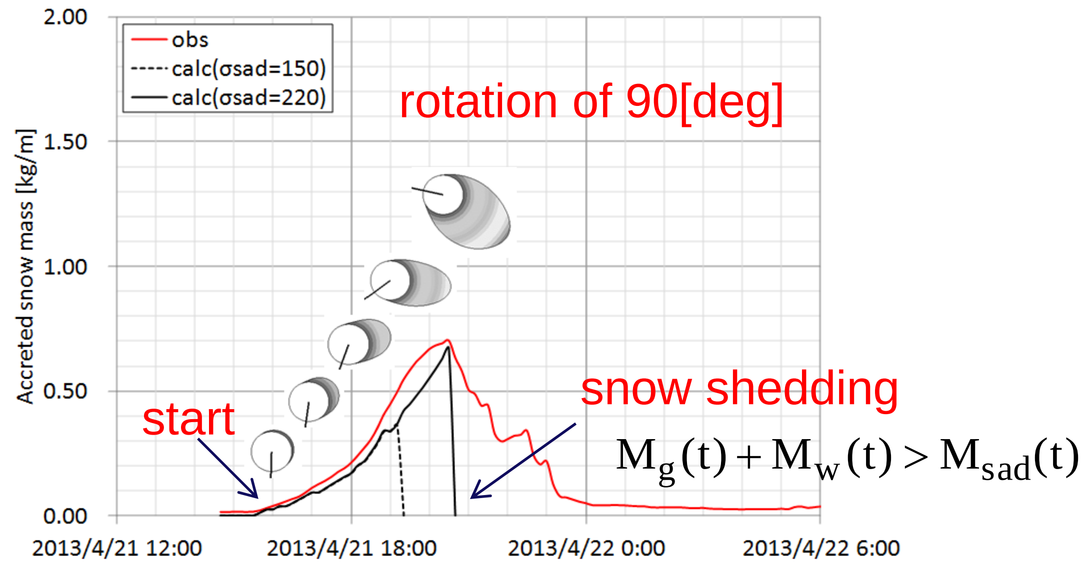


Conductor sampler spec and analytical condition

	Sampler1	Sampler2
type	ACSR240mm^2	ACSR810mm^2
Sampler length L_x	2[m]	
Sampler diameter	0.0224[m]	0.0384[m]
Torsional stiffness GJ	68.8[Nm^2/rad]	588[Nm^2/rad]
Equivalent span length 2L	90[m]	300[m]
Torsional spring constant	0.0680[Nm/rad]	0.0523[Nm/rad]
Azimuth	$\pi/8$	
Drag coefficient Cd	1	
Space division	Axial direction:10 Circumferential direction: 720	
Time division	1[s]	
Time step	36000	
$0°C$ height of atmosphere	250[m]	
Initial radius of snowflake	0.005[m]	
Parameter in snow density	ρ_0 = 500[kg/m^3]	
Maximum of tensile adhesive strength	σ_{tad} =300, 360[N/m^2]	
Maximum of shear adhesive strength	σ_{sad} =150, 220[N/m^2]	

Accretion on sampler1 (development on windward side)

	Observation	Simulation
16:00		
17:00		
18:00		
19:00		
20:00		



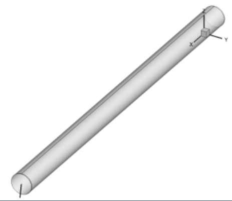
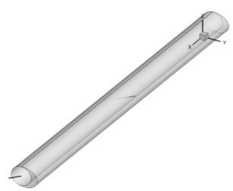
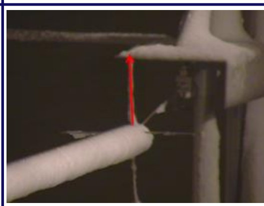
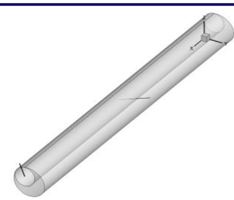
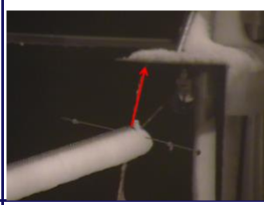
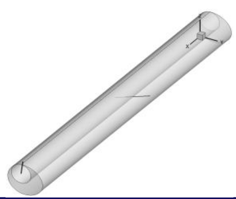
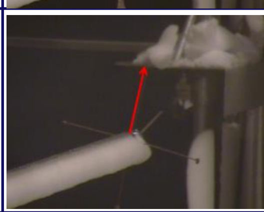
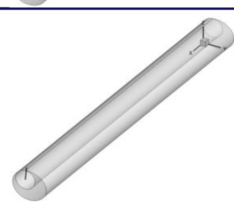
(1) Although the precipitation is observed from 14:50, snow accretion does not occur until 15:40 because LWC of snow deposit is over 0.4 and hence adhesive force is zero.

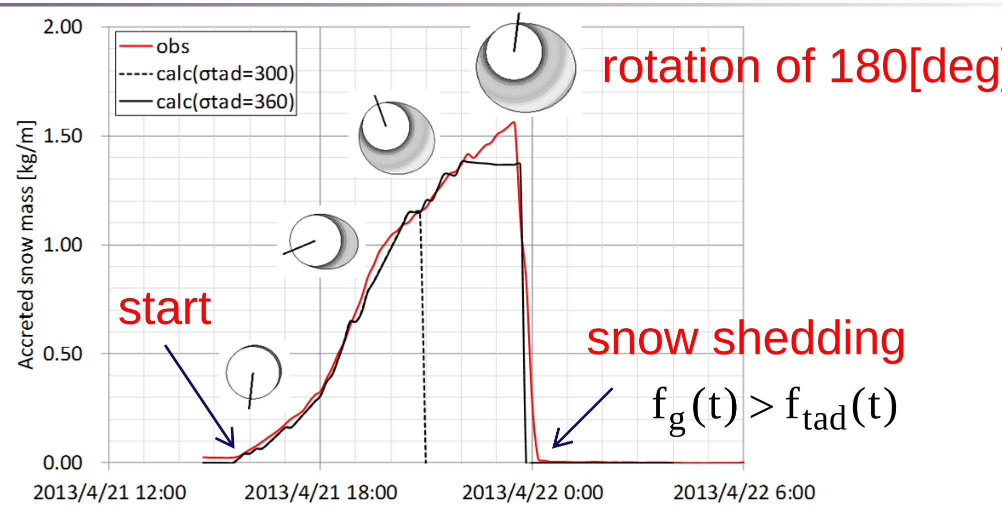
SNOVAL ver.3 can predict the start time of snow accretion.

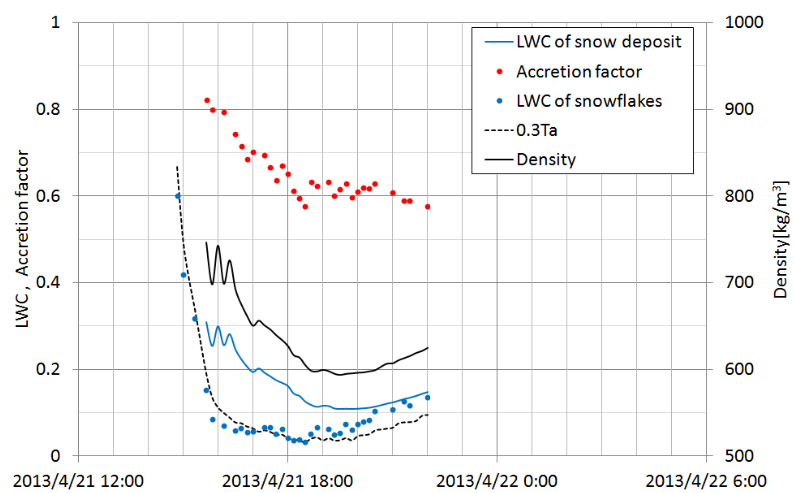
(2) Snow shedding starts at 20:30 and mass of accreted snow gradually decreases due to partial shedding.

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)

	Observation	Simulation
16:00		
18:00		
20:00		
22:00		
23:20		





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

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).