Field observations of snow damage to overhead transmission lines at the Kushiro test line

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Abstract— **Wet snow accretion on overhead lines often causes large-scale damage. The Kushiro test line, Japan, was constructed in 2013 for field observations of wet snow accretion in the conductor and insulators, and several cases of noticeable wet snow accretion and galloping of overhead lines was observed. In the most notorious case, more than 2 kg/m of snow was found to be accreted on the ACSR240 single conductor. In the case of single conductors without countermeasures, snow accretion developed to form a cylindrical sleeve with the wire rotation. However, this form of snow accretion also occurred in four-bundled conductors, where line spacers prevent the wire from rotating. This indicates that the accreted wet snow slides along the strands of the wire to form a cylindrical sleeve. Accordingly, the effectiveness of the snow resistance ring (the most used anti-snow-damage device in Japan) in preventing snow accretion was confirmed. As the ring prevents the accreted snow from sliding, accretion areas tend to split, causing the snow to be shed from the conductor. It was confirmed that greater heat transfer from the air to the snow and greater heat generated by the electric current facilitated the sliding of snow along the strand, making the snow resistance ring more effective.**

Keywords— ***Overhead transmission lines, Full-scale test lines, Wet snow accretion, Snow resistance ring, Heat balance***

I. Introduction

In Japan, heavy snow is one of the major natural phenomena that causes accidents of overhead transmission lines during the winter season. Many cases of large-scale snow damage have been caused by wet snow accretion on overhead lines [1, 2]. Wet snowflakes, which precipitate at a temperature of approximately 0 °C, contain some liquid water and easily accrete to the conductor. In the more serious cases, transmission towers may collapse due to the weight of heavily accreted snow and increased wind load owing to the increase in the wind projected area with snow accretion [3, 4]. In addition, the sagging of conductors owing to the weight of accreted snow can cause ground faults. Furthermore, sleet jumping and galloping on the conductor can induce short circuits. Sleet jumping is the phenomenon of a conductor jumping upward because of the accreted snow suddenly falling off. Galloping is an aerodynamic instability phenomenon, which is a large-amplitude and vertical-horizontal-torsional 3-DoF coupled oscillation, affected by the snow accretion shape and wind speed [5].

Field observations of full-scale transmission lines have been conducted to investigate the actual characteristics of snow accretion and the dynamic response of the lines due to galloping and sleet jumping. However, because the climate conditions that induce significant snow accretion rarely occur, the amount of collected data is inadequate. Furthermore, the effectiveness of various countermeasures, which have been developed to prevent or reduce snow damage, can vary depending on the meteorological conditions, and more systematic and detailed data collection is required. Consequently, to determine the damage caused by ice and snow on electric power transmission facilities since 2007, the Central Research Institute of Electric Power Industry (CRIEPI), in collaboration with ten major electric companies in Japan, initiated a research project and conducted field observations of wet snow accretion and in-cloud icing, including the resultant galloping [6, 7, 8]. At the beginning of the research project, observations on overhead transmission lines under various snow types and wind conditions were conducted at several sites across the country. Then, to obtain focused data on wet snow accretion under moderate to strong winds, a full-scale test facility was constructed in Kushiro, where severe wet snowfall events frequently occur. Accordingly, the observations across Japan have gradually been focused on this site.

This study presents the observation results of several cases of noticeable wet snow accretion at the Kushiro test line. The amount of snow accretion was compared between lines with different countermeasures. The meteorological and structural conditions, under which the countermeasure effects are likely to occur, are discussed by comparing the results for several cases.

II. Overview of the Kushiro test line

The Kushiro test line was constructed in 2013 in Kushiro City, Hokkaido, Japan, to enable field observations of galloping in overhead lines and wet snow accretion on conductors and insulators. Fig. 1 shows the location of the Kushiro test line and an example weather chart for a snow event. During the most severe snowfall events at this site, low pressure developed on the southern Hokkaido shore and approached the study site, and precipitation at approximately 0 °C, which is conducive to snow accretion, continued under moderate to strong winds.

Fig. 2 shows several pictures of the Kushiro test line, and Table 1 shows the observation dataset as of the winter of 2021. The test line consists of three towers that are currently connected by two phases of four-bundled conductors and 11 phases of single conductors. The test line extends at 115° in the azimuthal direction. In the lower arm, the span length is approximately 300 m; in the middle and upper arms, the span length is approximately 400 m. Two of the single conductors are characterized by the ability to investigate the effect of current-generated heat (direct current (DC): up to 400 A) on snow accretion development. The test line also includes meteorological and simplified instruments for observing snow accretion in various insulators and conductor models.

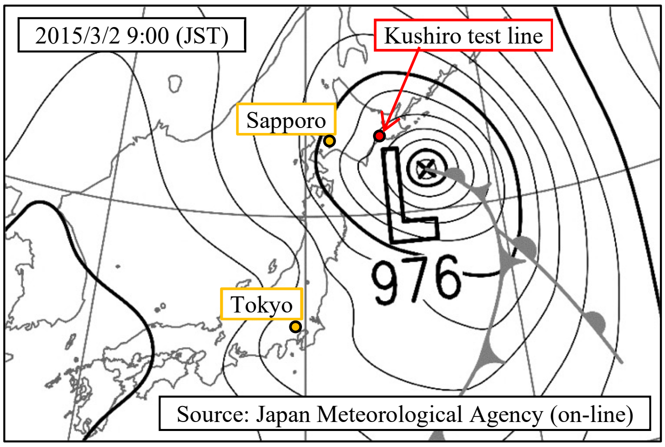
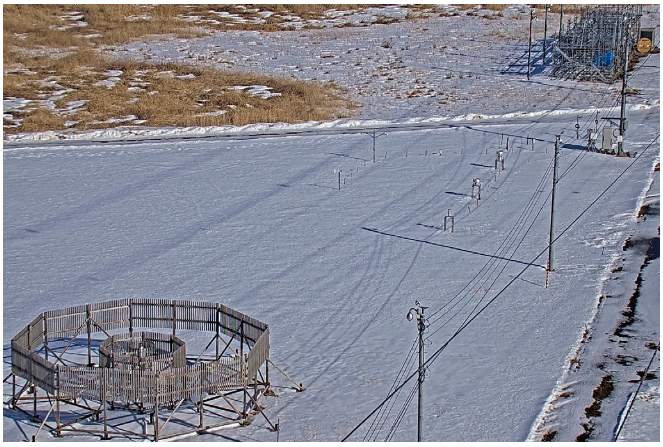


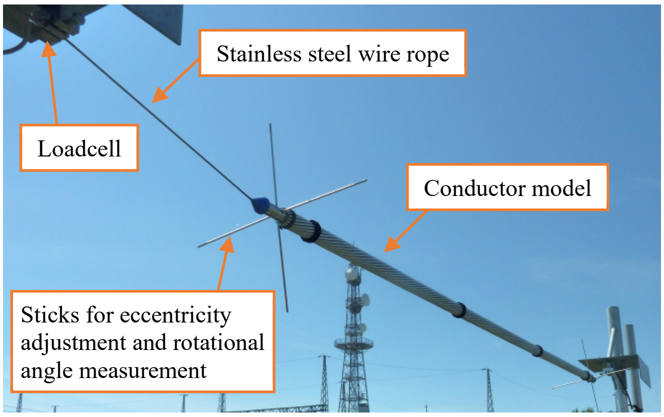
Fig. 1 Location of the Kushiro test line overlaid on a typical weather chart for a wet snow event

(a) Full-scale test lines



(b) Installation area of meteorological instruments

(c) Conductor models on the ground (h = 4 m)



(d) Conductor model for snow accretion observation

(e) Insulators for snow accretion observation (h = 10 m)

Fig. 2 Pictures of the Kushiro test facility

Table 1 Observation data (as of winter 2021)

Observation data	**Specification**
Conductor tension	Via loadcell at support points
Full view and snow accretion images	From towers, observation poles, and spacers
Conductor displacements and angles	By analysing the LED marker and reflective plate images at quarter and half of the span
Amount of snow accretion	Via calculation from tension for full-scale lines, by directly measuring for wire models and insulators
Temperature of conductor surface	Via a thermistor-type thermometer stuck on the conductor surface
Wind speed and direction	$h = 1.5, 11, 22, 44$ m
Air temperature	$h = 1.5, 4.0, 44$ m
Relative humidity	$h = 4.0, 44$ m
Atmospheric pressure	$h = 1.5$ m
Precipitation	Via a tipping bucket rain gauge with/without a cylindrical windshield and weighing the bucket rain gauge with a double fence
Precipitation conductivity	Via one of the rain gauges
Snowfall drop size distribution and velocity	Via two-dimensional video disdrometer in the double fence
Radiation balance	Long/short, upward/downward
Snow depth	Via an ultrasonic snow depth gauge
Soil moisture and temperature	Underground: $h = -6, -25, -70, -92, -120, -145$ cm

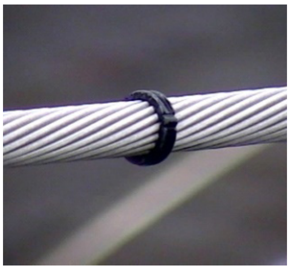
* h: height above ground level (agl)

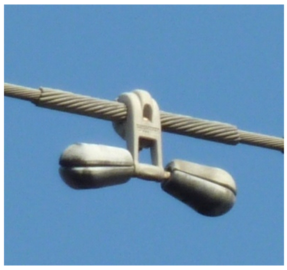
Thorough observations have been conducted since the winter of 2014, and measurement instruments were added and changed based on the observation results and other factors. In the latter observations, the altitudinal distributions of air temperature and wind speed were measured. Furthermore, conductor models for simple snow accretion observations were installed on the ground ($h = 4.0$ m) and towers ($h = 26, 44$ m) (h: height above ground level (agl)) to investigate the effect of slight differences in meteorological conditions on the snow accretion rate. The conductor model consisted of the outermost layer of an actual conductor wrapped around a stainless-steel shaft. Because snow accretion develops with the rotation of the conductor, the rotational rigidity of the models was adjusted by varying the length and diameter of the stainless-steel wire ropes to simulate the snow accretion characteristics in the middle of the actual lines. For precipitation measurements, the Double-Fence International Reference (DFIR) [9] recommended by the World Meteorological Organization (WMO) was used as a reference to compare the catch ratio of snow under the effect of wind with a tipping bucket rain gauge, typically used in Japan.

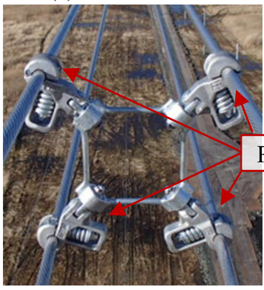
III. Countermeasures Installed in Full-Scale Lines

The amount of snow accretion and the dynamic response of the lines due to galloping were compared between lines with different countermeasures. Some of the installed countermeasures are shown in Fig. 3 and listed in Table 2. The effects of snow resistance (SR) rings and counterweights have been investigated for single conductors, and the effect of current-generated heat (DC: 150 A) on snow accretion development was investigated for two single conductors (Phases D and E). SR rings and counterweights are commonly used countermeasures in Japan to prevent or reduce wet snow accretion [10]. Excessive snow accretion forms a cylindrical sleeve around the conductor. Cylindrical snow sleeves develop via two different mechanisms: first, the accreted snow slides along the strands of the wire; second, the wire rotates owing to the moment caused by the snow accretion weight. The SR ring is a plastic ring that prevents accumulated snow from sliding along twists on the conductor surface, thus preventing excessive cylindrical snow accretion. A counterweight is an eccentric weight that discourages conductor rotation, thereby preventing excessive cylindrical snow accretion. However, it has been pointed out that suppressing the conductor rotation might increase the incidence of galloping, owing to the tendency of snow accretion to develop in a single direction [7].

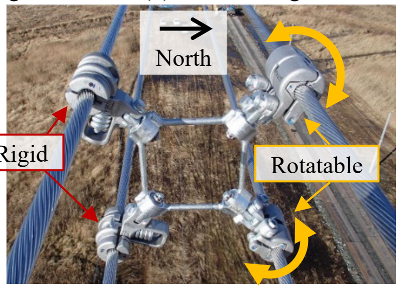
Regarding the four-bundled conductor lines, one is a non-countermeasure phase with normal spacers and the other is a countermeasure phase with loose spacers. Line spacers are installed to maintain the spacing of sub-conductors and normal spacers, which bundle sub-conductors and typically bear rigid clamps, making it more difficult for the sub-conductors to rotate. Therefore, normal spacers are considered effective in reducing snow accretion to some extent. However, owing to conductor rotation suppression, galloping is more likely to occur in multi-bundled conductors than in single conductors. Loose spacers have been developed as anti-galloping devices. Loose spacers bear certain rotational and rigid clamps. The rotation angle of the rotational clamps was limited to $\pm 80°$ from the equilibrium position. Loose spacers potentially suppress galloping by ensuring that the snow accretion on the rotatable sub-conductor is more circular (less eccentric) than that on the rigid sub-conductor.


(a) Snow-resistance ring


(b) Counterweight



(c) Normal spacer



(d) Loose spacer

Fig. 3 Countermeasures installed in full-scale test lines

Table 2 Specifications of some of the installed countermeasures

Location	Conditions	Name	Countermeasure
Lower arm ($h = 25$ m at one end, $h = 16$ m at the other, $l = 293$ m)	Single conductor, ACSR240mm^2	Phase A	None
		Phase B	SR rings
		Phase C	SR rings + counterweights
		Phase D	SR rings + DC 150 A
		Phase E	None + DC 150 A
Upper arm ($h = 40$ m at both ends, $l = 394$ m)	Four-bundled conductor, ACSR410mm^2	1L	Normal spacers
		2L	Loose spacers

* h: height agl, l: span length

IV. Observation Results for the Winter of 2014

Several cases of wet snow accretion and galloping have been observed until the winter of 2021. This study focuses on wet snow accretion cases that occurred in the winter of 2014. Although approximately only one significant wet snow accretion case per year is observed at this site on average, four cases were observed in the winter of 2014 alone.

Table 3 shows the maximum amount of snow accretion and the meteorological data statistics for the four cases in which snow accretion occurred in the winter of 2014. In addition, Fig. 4 and 5 show the time series of the meteorological data, amount of snow accretion, and rotation angle at the centre of the span for Cases 1 and 3, respectively. Here, precipitation was measured by a tipping bucket rain gauge with a cylindrical windshield; air temperature and relative humidity were measured at 4.0 m agl; wind speed and direction were measured at 11.0 m agl; the amount of snow accretion was calculated from the tension of each line by considering the effect of temperature and wind load; and the rotation angle of a single conductor was obtained via image analysis, although data are missing for some periods when the targets could not be recognized in the image.

Table 3 Overview of snow accretion cases in the winter of 2014

Case	Date	Maximum amount of snow accretion [kg/m] Phase A (None)	Phase B (Ring)	Phase C (Ring + CW)	Phase D (Ring + 150 A)	Phase E (None + 150 A)	1L (Normal SP)	2L (Loose SP)	Total precipitation [mm]	Mean air temperature [°C]	Mean relative humidity [%]	Mean wind speed [m/s]	Mean wind direction [°]
1	2014/12/16	1.16	1.15	0.97	0.98	1.39	0.63	0.71	29.5	0.20	97.0	5.0	-27.4
2	2015/02/27	0.78	0.68	0.26	0.58	0.63	0.80	0.76	21.0	0.29	97.4	5.1	7.8
3	2015/03/01	2.12	1.70	0.40	0.50	0.84	1.91	1.86	52.5	0.33	97.8	3.7	-27.7
4	2015/03/04	0.32	0.33	0.24	0.42	0.40	0.21	0.28	8.0	0.06	94.3	5.9	-27.8

* The meteorological data statistics is for the period for which snow accretion developed in Phase A.
* Wind direction is the angle relative to the line orthogonal direction (25° azimuth).

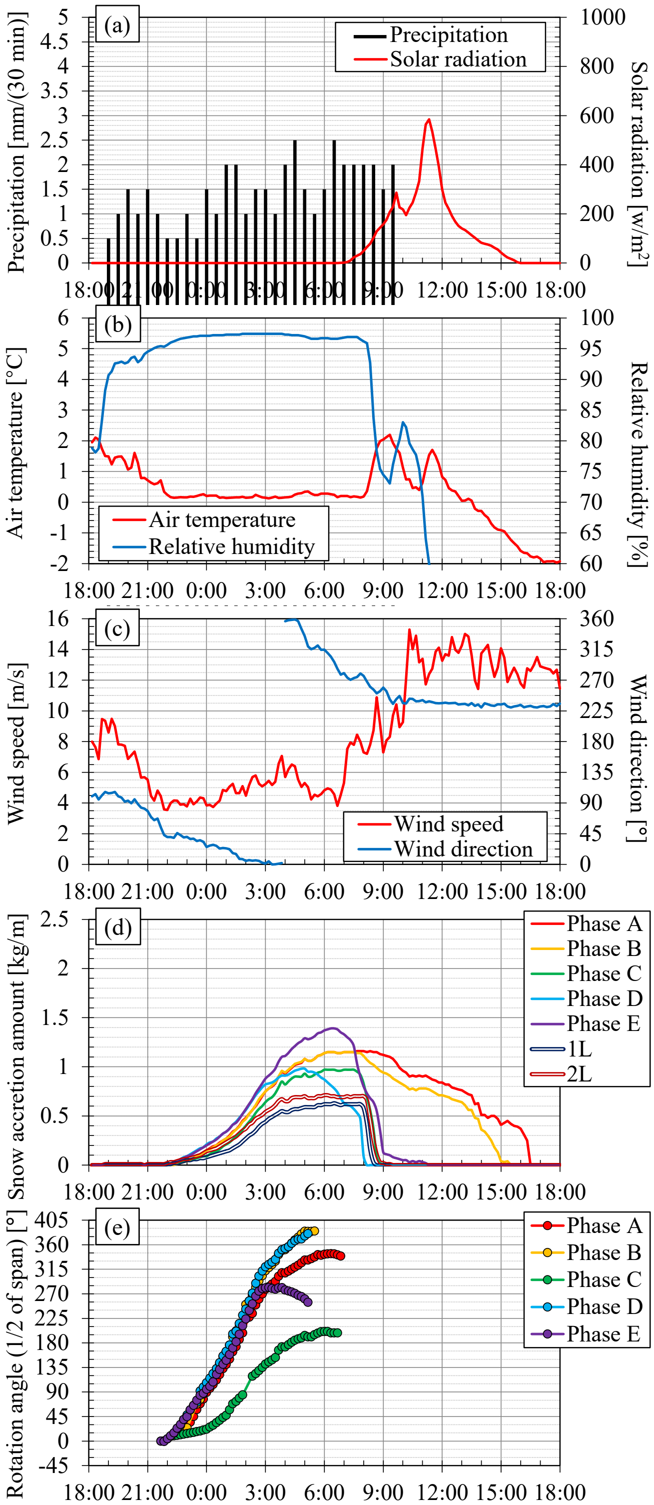


Fig. 4 Time series of statistical values for Case 1 (2014/12/16–17)

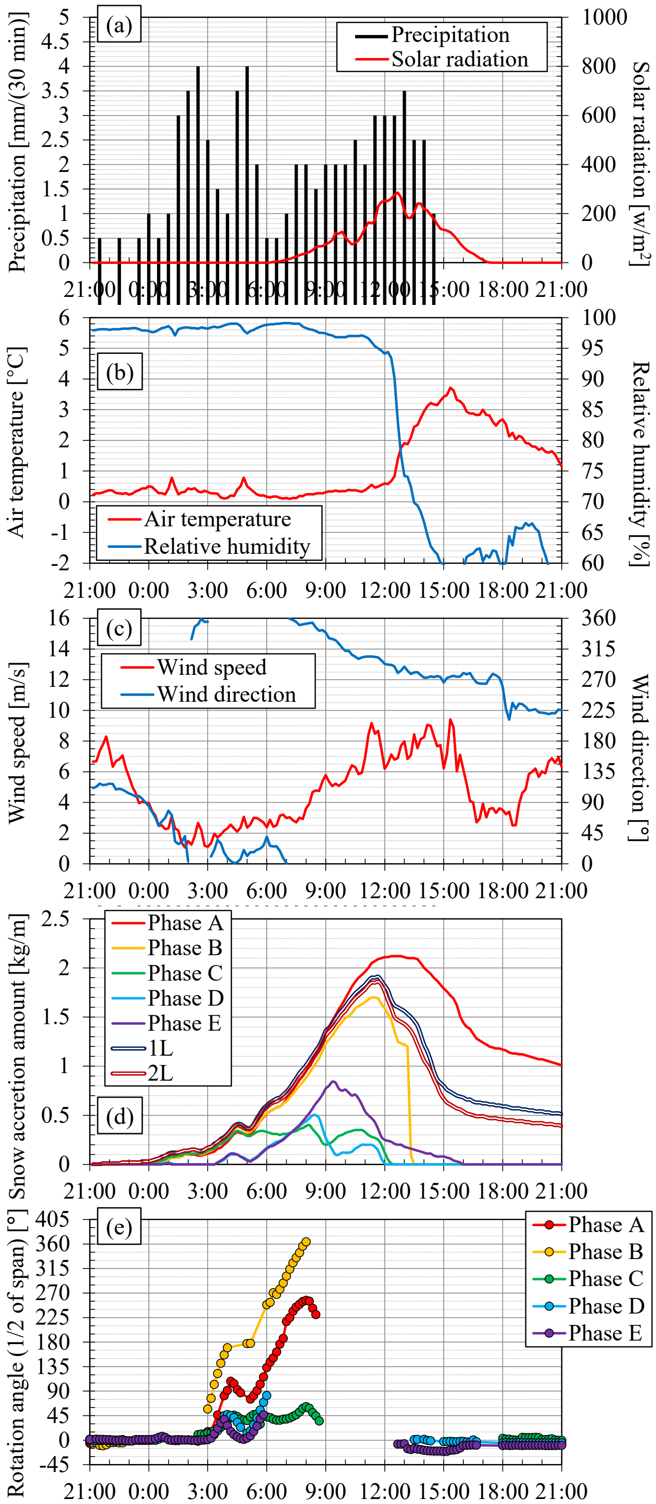


Fig. 5 Time series of statistical values for Case 3 (2015/3/1–2)

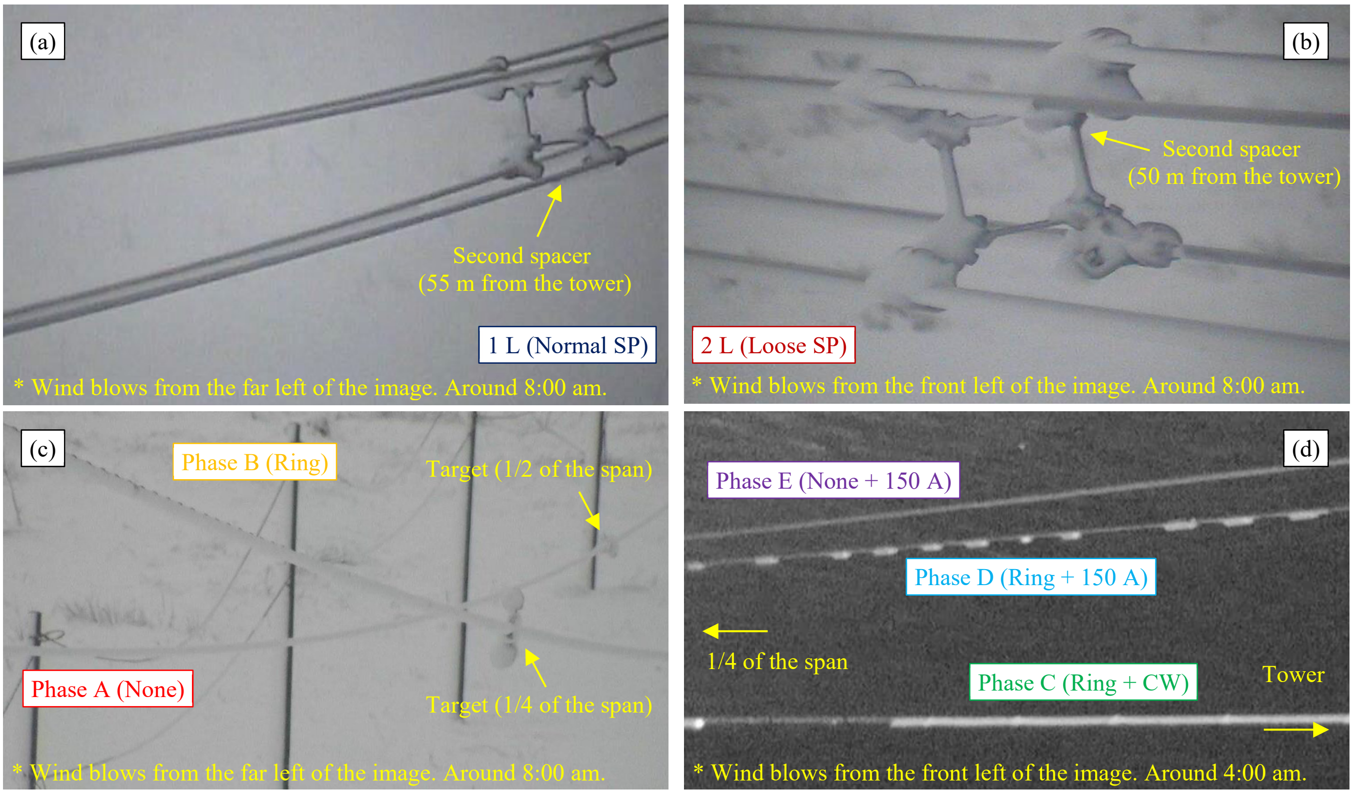


Fig. 6 Examples of snow accretion on the respective lines (Case 1: 2014/12/16–17)

Fig. 6 and 7 show the snow accretion situations in Cases 1 and 3, which are termed as particularly remarkable cases. All observed cases of wet snow accretion in 2014 occurred in the moderate wind speed class (3–8 m/s [7]) at temperatures slightly above 0 °C and at a relative humidity in the range of 90–100%. Although the four cases had similar meteorological conditions, the effectiveness of countermeasures differed. The following discussion focuses on the different effects of countermeasures in these cases and discusses the conditions under which the effects of countermeasures are likely to appear. It should be noted that no significant galloping was observed in the cases presented in this study.

A. Situation in Case1 (2014/12/16–17)

In Case 1, snow accretion occurred in the line from 12/16 at 22:00 to 12/17 at 8:00, while precipitation continued at temperatures around 0–0.5 °C, as shown in Fig. 4. A comparison of Phases A–C, where the direct current was not passed, shows that this is a case in which the effects of the countermeasure were small. In Phase B, where SR rings were installed, the maximum amount of snow accretion was almost the same as that in Phase A, where no countermeasures were installed. Fig. 6(c) shows the snow accretion situation at a certain time in Case 1. In Phases A and B, although the image was taken from the downwind side, snow covered the wires, suggesting the formation of a cylindrical snow sleeve. As shown in Fig. 4(e), the wire rotated 360° at the centre of the span at approximately 6:00; thus, the cylindrical snow sleeve formed mainly because of the rotation of the wires. As shown in Fig. 6(d), in Phases C and B, snow almost uniformly covered the SR ring, suggesting that the effect of the SR ring was weak in these phases. Fig. 4(e) shows that the wire rotates by approximately 180°, even in phase C, and even with counterweights. Thus, the snow accretion reduction effect of counterweights was also small in this case.

Owing to the effect of the current-generated heat (DC: 150 A, 2.7 W/m), the amount of snow accretion was larger in Phase E than that in Phase A but smaller in Phase D than that in Phase B. This result indicates that the effect of the SR ring is greater with current-generated heat. As shown in Fig. 6(b), in phase E, without SR rings, snow accretion occurred uniformly on the wires, and it is assumed that a cylindrical snow sleeve formed. However, in Phase D, the accreted snow was divided by the SR rings, indicating that the snow had started to shed from the wire.

While the wire diameter difference should be considered when comparing the amount of snow accretion on the four-bundled conductor lines, the amount of snow accretion in 1 L with the normal spacers was considerably less than that in single-conductor Phase A. In Fig. 6(a), it can be observed that there was no accreted snow on the downwind side of the sub-conductors, suggesting that the spacers suppressed their rotation, thus reducing the amount of snow accretion. The maximum amount of snow accretion in 2 L with loose spacers was slightly higher than that in 1 L, which could be attributed to the fact that sub-conductors with the rotatable clamps can rotate.

B. Situation in Case 3 (2015/3/1–2)

In Case 3, where the most significant snow accretion was observed, snow accreted the line from 3/1 at 0:00 to 12:00, while precipitation continued at temperatures around 0–1 °C, as shown in Fig. 5. In Phase A, more than 2 kg/m of snow accreted on the wire, while in Phase B the maximum amount of snow accretion was reduced by approximately 20%. As shown in Fig. 7(c) and (d), a cylindrical snow sleeve formed in Phase A, but the accreted snow was divided by the SR rings,

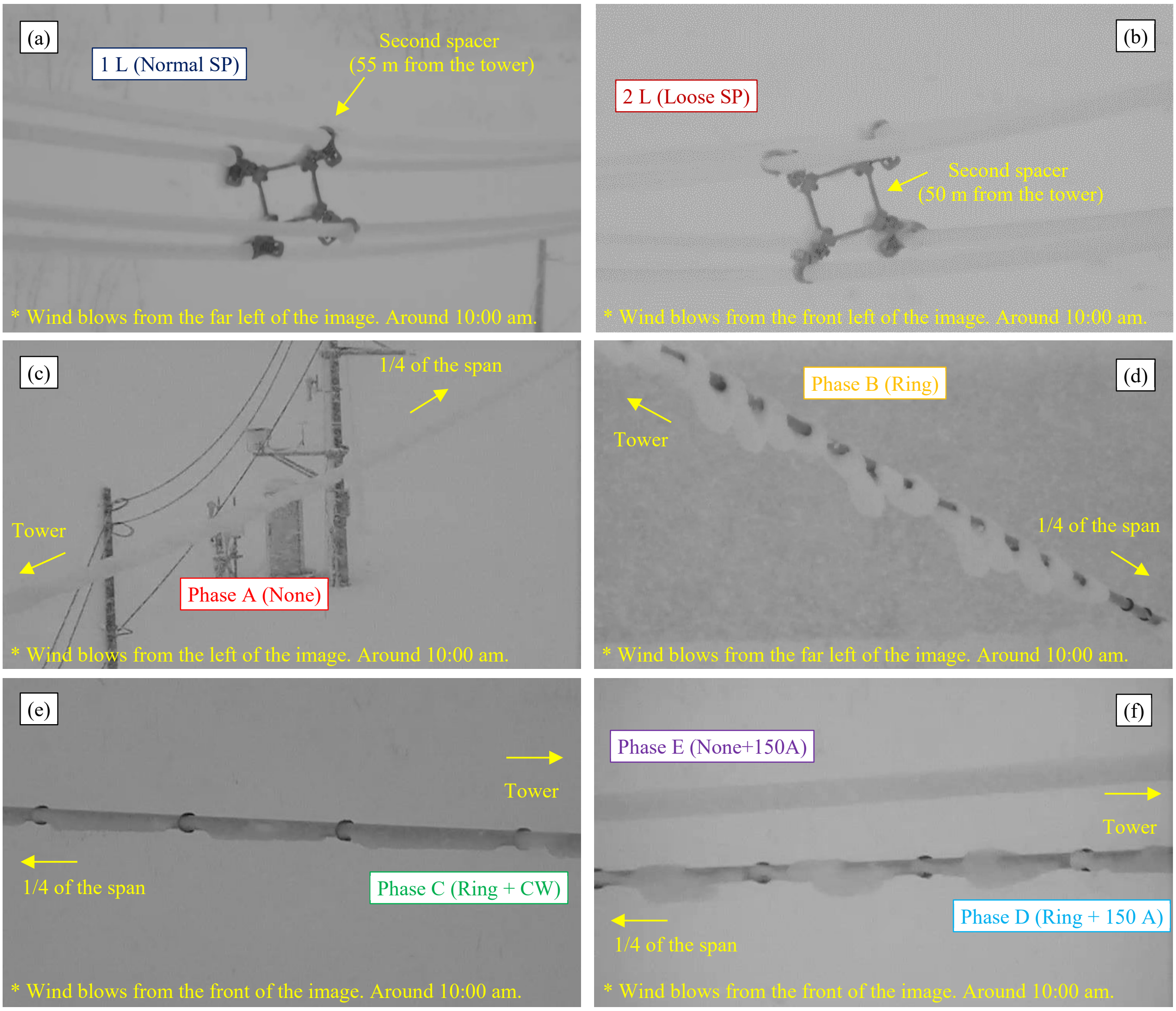


Fig. 7 Examples of snow accretion on the respective lines (Case 3: 2015/3/1–2)

and the snow tended to shed from the wire in Phase B. However, it was also observed that much of the hanging snow remained on the wire. In addition, the amount of snow accretion in Phase C was significantly reduced, and the maximum value was reduced by over 80% compared to Phase A. As shown in Fig. 7(e), the snow accretion on the wire in Phase C was significantly less than that in Phases A and B, and snow division by the SR ring was also observed. Furthermore, as shown in Fig. 5(e), the rotation angle of the wire is small in this case; because of the counterweights and SR rings, the accreted snow repeatedly shed and did not reach a certain amount.

Owing to the effect of the current-generated heat, the amount of snow accretion was much smaller in Phases E and D than that in Phases A and B. Furthermore, owing to the effect of the SR rings, the maximum amount of snow accretion in Phase D was reduced to about 40% compared to that in Phase E. This result also indicates that the effect of the SR ring is greater with current-generated heat. As shown in Fig. 7(f), while a cylindrical snow sleeve formed in Phase E, the accreted snow was divided by the SR rings in Phase D, and it is assumed that some of the accreted snow shed by the SR rings.

As shown in Figs. 7(a) and (b), snow covered all sub-conductors, suggesting that accreted snow developed as a cylindrical snow sleeve even on the four-bundled conductor lines. As the line spacers (normal and loose spacers) prevented the sub-conductors from rotating, accreted wet snow slid along the strands of the wire to form a cylindrical sleeve. It should be noted that no SR rings existed in these four-bundled conductor lines. The amount of snow accretion of 1 L and 2 L was almost the same, regardless of the type of line spacer.

V. Discussion on the Effect of Countermeasures

As indicated in the previous section, the effectiveness of the countermeasures differed between the two wet snow accretion cases investigated in this study. In Case 1, the accreted snow hardly slid along the strands of the wire, whereas in Case 3, the accreted snow slid easily. The sliding behaviour of accreted snow is dependent on the water content of the accreted snow. In other words, accreted snow slides more easily if it is subjected to a large amount of heat from the outside and thereby, melts to some extent. The heat transfer from the air to the snow is greater when the temperature, humidity, and wind speed are higher. Furthermore, solar radiation also affects snow melting and sliding. In Case 3, the melting of the accreted snow due to heat transfer from the air and the effect of solar radiation is greater than that in Case 1; the snow easily slides along the strands of the wire and induces the formation of a cylindrical snow sleeve on the four-bundled conductor without SR rings. In contrast, in cases where the snow is easily slidable, the effect of the SR ring is more likely to occur, and if the rotation of the wire is also suppressed by counterweights, a significant countermeasure effect against snow accretion is achieved. Similarly, greater heat generated by the electric current facilitates the sliding of the snow along the strand, making the SR rings more effective.

However, in Case 1, where the accreted snow sliding was difficult and the adhesion force on the wire was probably strong, the wire rotated by a relatively large degree even with the use of counterweights. Although this may be a specific case, it may be necessary to increase the number or weight of counterweights to prevent wire rotation under such conditions. The installation of line spacers reduced the amount of snow accretion in the four-conductor wires, where the wire rotation prevention effect was higher, proving the importance of wire rotation prevention in reducing the amount of snow accretion, even in this case.

Compared with other cases, including those observed in years other than 2014, the two cases described here might be unusual. Further analyses should include other cases. However, these unusual cases have allowed for the identification of when SR rings are more likely to be effective.

VI. Conclusions

The Kushiro test line, a full-scale test facility, was constructed for field observations of wet snow accretion on conductors and insulators and galloping in overhead lines. Herein, the features of the facilities and typical observation results for wet snow accretion on conductors are presented. In addition, the effects of countermeasures on reducing the amount of snow accretion are discussed via observations.

In the case of single conductors without countermeasures, snow accretion develops as a cylindrical sleeve with wire rotation. Therefore, countermeasures to prevent wire rotation, such as counterweights, are effective. However, in a certain wet snow case, snow accretion developed as a cylindrical sleeve, even in four-bundled conductors where line spacers prevented the wire from rotating. This indicates that the accreted wet snow slides along the strands of the wire to form a cylindrical sleeve. Melting of the accreted snow, caused by heat transfer from the air and the effect of solar radiation, makes it easy for the accreted snow to slide along the strand on the wire surface and induces the formation of a cylindrical snow sleeve without SR rings. However, snow tends to shed from the wire in the presence of SR rings. Moreover, it was also observed that the heat generated by the electric current in the conductor accelerates this effect. Furthermore, the effect of SR rings is more likely to occur if counterweights suppress wire rotation.

In future work, to clarify the differences in the countermeasure effects between the metrological conditions in detail, we intend to model the heat balance around the accreted snow and evaluate each effect quantitatively for typical wet snow cases. Furthermore, observations in the Kushiro test line will continue to clarify the mechanism of snow damage, including galloping, and to verify the effectiveness of the countermeasures adopted.

Acknowledgment

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