

1 **Field observations of wet snow accretion on overhead transmission lines at the Kushiro test line**

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11 **Abstract**

12 Wet snow accretion on overhead lines often causes large-scale snow damage. The Kushiro test line, Japan, was constructed
13 in 2013 for field observations of wet snow accretion in conductors and insulators as well as galloping resulting from snow
14 accretion in overhead lines. Several cases of noticeable wet snow accretion have been observed at this site, especially in the
15 winter of 2014. In the most notorious case, more than 2 kg/m of snow was found to be accreted on the ACSR240 single
16 conductor, which has a diameter of 22.4 mm. In the case of single conductors without countermeasures, snow accretion
17 developed to form a cylindrical sleeve with wire rotation. However, in some cases, the cylindrical sleeve of snow accretion
18 also occurred in four-bundled conductors, where line spacers prevent the wire from rotating. This indicates that the accreted
19 wet snow slides along the strands of the wire to form a cylindrical sleeve. Accordingly, the effectiveness of the snow
20 resistance ring, which is the most commonly used anti-snow-damage device in Japan, in preventing snow accretion was
21 confirmed. As the ring prevents the accreted snow from sliding, accretion areas tend to split, causing the snow to be shed
22 from the conductor. More heat transfer from the air to snow and heat generated by the electric current facilitated the sliding
23 of snow along the strand, making the snow resistance ring more effective.

24

25 **Keywords**

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

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28 **1. Introduction**

29 Atmospheric icing on overhead transmission lines sometimes causes significant damage and leads to massive power outages.

30 Atmospheric icing is typically classified into two categories according to its developmental process: in-cloud icing and

31 precipitation icing (CIGRE, 2006; Farzaneh, 2008). In-cloud icing occurs in clouds containing supercooled droplets that

32 remain in the liquid phase at temperatures below 0 °C; therefore, in-cloud icing is likely to occur in high-altitude

33 transmission lines. In contrast, precipitation icing is caused by freezing rain and wet and dry snow and occurs even in flat

34 areas at low altitude. Many cases of large-scale snow damage in Japan have been caused by wet snow accretion on overhead

35 lines (Sakamoto, 2000; Wakahama et al., 1978). Wet snowflakes, which precipitate at a temperature of approximately 0 °C

36 with high relative humidity, contain some liquid water and easily accrete to the conductor (Makkonen, 1989; Makkonen and

37 Wichura, 2010; Nygaard et al., 2014). Wet snow can fall even at higher temperatures if the relative humidity is lower

38 (Matsuo et al., 1981), and a positive range of wet bulb temperatures is considered to correspond approximately to these

39 conditions (Makkonen, 1989). Moreover, wet snow accretion is characterised by its occurrence even under strong winds,

40 whereas dry-snow accretion occurs only under weak-to-calm winds. In more serious cases, transmission tower collapse may

41 occur due to the weight of heavily accreted snow and increased wind load owing to the increase in the wind projected area

42 with snow accretion (Matsumiya et al., 2021). Additionally, sagging of conductors because of the weight of accreted snow

43 can cause ground faults. Furthermore, ice shedding (snow shedding) and galloping on the conductor can induce short

44 circuits. Snow shedding refers to a conductor jumping upward when the accreted snow suddenly falls off (Jamaledine et al.,

45 1993; Fekr and McClure, 1998). Galloping is an aerodynamic instability phenomenon that is a large-amplitude and

46 vertical-horizontal-torsional three-degree-of-freedom coupled oscillation affected by the snow accretion shape and wind

47 speed (EPRI, 1979; CIGRE, 2007). In addition to in-cloud icing at the transmission lines in high-altitude areas, galloping

48 sometimes occurs due to wet snow accretion at the transmission lines in flat areas.

Field observations of full-scale transmission lines have been conducted to investigate the actual characteristics of snow accretion and dynamic response of the lines due to galloping and snow shedding. 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 structural and meteorological conditions; more systematic and detailed data collection is required. This is because the development of wet snow accretion is highly dependent on the rotating behaviour (rotational stiffness) of the wire (McComber, 1984; Skelton and Poots, 1991) and sliding behaviour of the accreted snow on the wire surface (Minyu et al., 1984); the latter depends on the wetness of the accreted snow. 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 electrical companies in Japan, initiated a research project (Shimizu et al., 2017) and conducted field observations of wet snow accretion (Matsumiya et al., 2019) and in-cloud icing (Matsumiya et al., 2012, 2022a), including the resultant galloping. At the beginning of the research project, observations of 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 occur frequently (Nishihara et al., 2017a). Accordingly, the observations in Japan have gradually been focused at this site.

This study presents the observation results of several cases of noticeable wet snow accretion at the Kushiro test line. First, the specifications of the Kushiro test line, measurement instruments, and countermeasures installed in the test line are presented. Then, the observation results are presented for the winter of 2014, when several cases of noticeable wet snow accretion were observed. Finally, the amounts of snow accretion are compared between lines with different countermeasures. In addition, the meteorological conditions under which the countermeasure effects are likely to occur are discussed by comparing the results for several cases.

2. 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 (Nishihara et al., 2017a). Figure 1 shows the location of the Kushiro test line and an example weather chart for a snow event. During the severe snowfall events at this site, low pressure develops on the southern Hokkaido shore and approaches the study site, and precipitation occurs at approximately 0 °C, which is conducive to snow accretion, under moderate to strong winds.

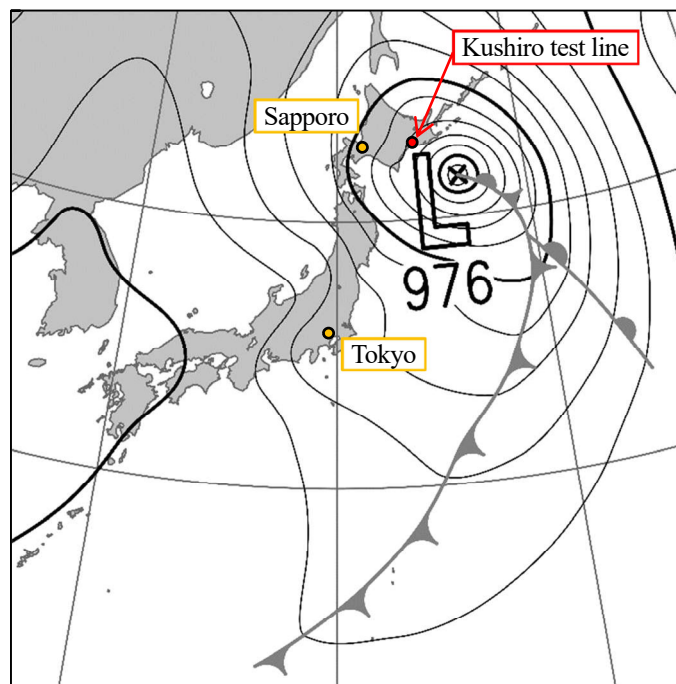
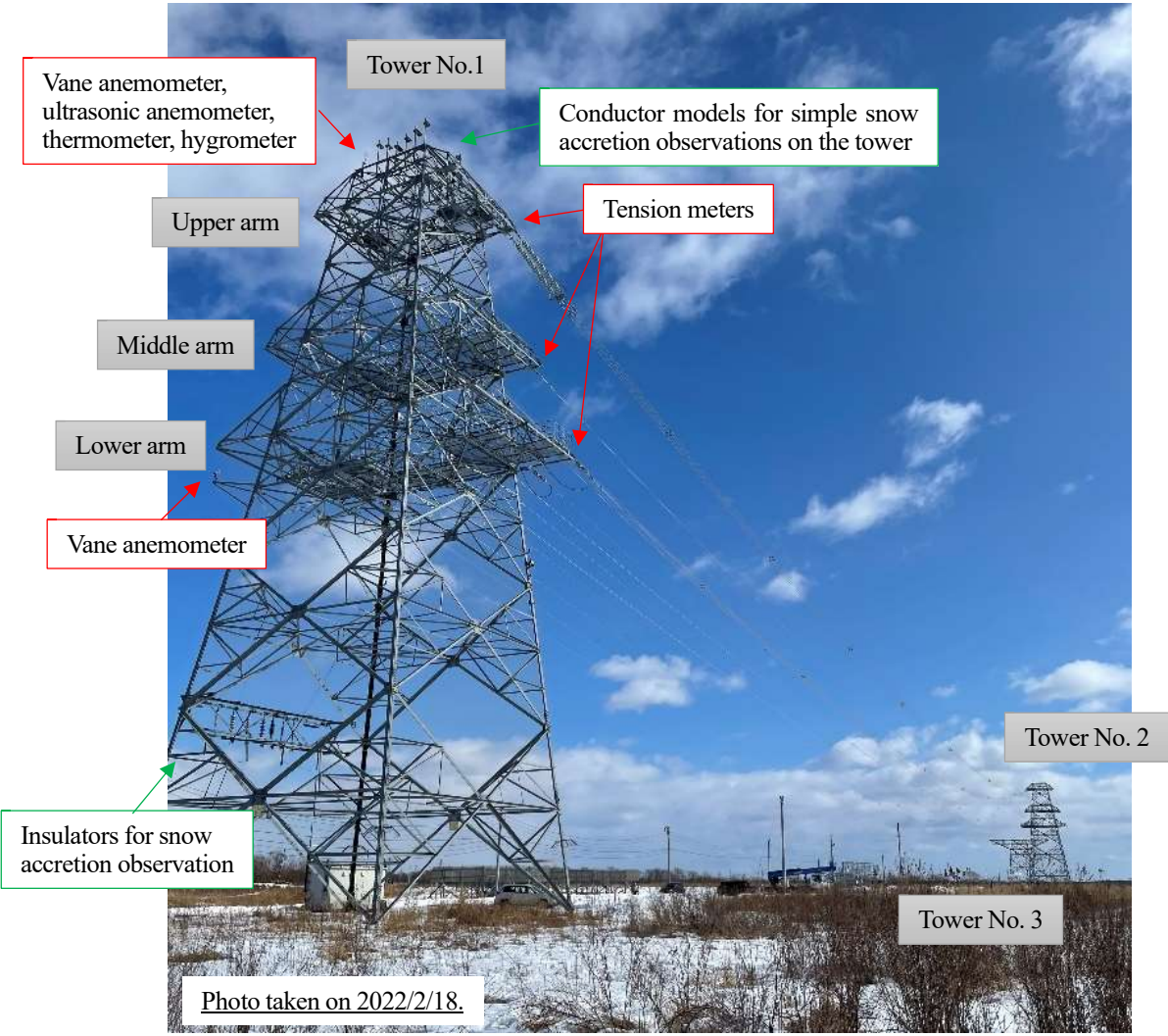


Figure 1 Location of the Kushiro test line overlaid on a typical weather chart for a wet snow event during observation period (2015/3/2 9:00 JST, source: Japan Meteorological Agency (online))

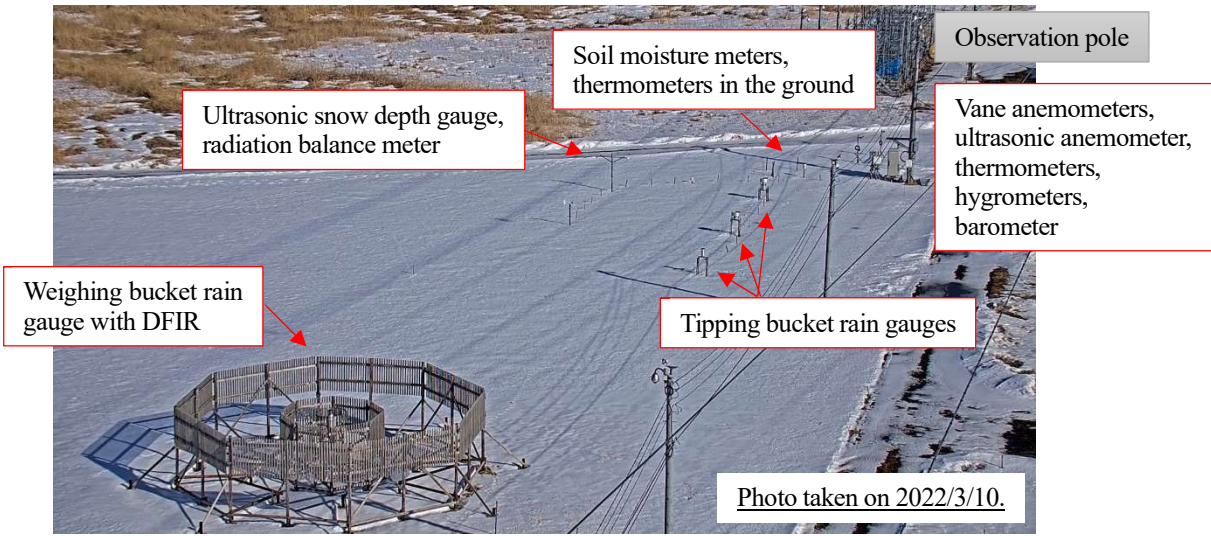
Figure 2 shows the main features of the Kushiro test line, which consists of three towers that are currently connected by two phases of four-bundled conductors (between the upper arms of Towers No. 1 and No. 2) and 11 phases of single conductors (between the middle arms of Towers No. 1 and No. 2, and between the lower arms of Towers No. 1 and No. 3). The test line extends at 115° in the azimuthal direction. In the lower arms, the span length is approximately 300 m, and in the middle and upper arms, it is approximately 400 m. Two of the single conductors are characterised by the ability to investigate the effect of current-generated heat (direct current (DC) up to 400 A) on snow accretion development.

Moreover, the test line includes various meteorological instruments. Thorough observations have been conducted since the winter of 2014, and measurement instruments were added and changed based on the observation results and other

88 factors. Table 1 shows the observation dataset of the winter of 2021. In the latest observations, the altitudinal distributions of
89 wind speed, air temperature, and relative humidity were measured. For precipitation measurements, the Double-Fence



(a) Full-scale test lines



(b) Installation area of meteorological instruments
Figure 2 Main features of the Kushiro test facility

International Reference (DFIR) recommended by the World Meteorological Organization (WMO) (Goodison et al., 1998) was used as a reference to compare the catch ratio of snow under the effect of wind, with the tipping bucket rain gauge typically used in Japan. A two-dimensional video disdrometer, which can measure the snowfall drop size distribution and velocity, is set in another double fence. Furthermore, snow accretion can be observed by web cameras installed on the towers and observation poles. Infra-red floodlights were installed so that the snow accretion characteristics can also be identified to a certain extent at night. As the light-emitting diode (LED) markers were installed in the one-quarter and half positions of the span, the vertical, horizontal, and torsional displacements of the line were obtained by analysing the images captured using the web cameras. Thermistor-type thermometers were stuck on some of the conductors to measure the temperature of the conductor surface. Moreover, cameras were set at the spacers in the span to capture the images and identify the snow-accreted conditions for bundled conductors.

Table 1 Observation data (Winter of 2021)

Observation data	Specification
Conductor tension	Via load cell 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 conductor 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 bucket rain gauge with 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

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Figure 3 shows the simplified instruments for observing snow accretion in various conductors and insulators. The simplified observation instruments for snow accretion on a conductor consisted of a dummy conductor, stainless-steel wire ropes, load cells, and web cameras. The dummy conductor consisted of the outermost layer of an actual conductor wrapped

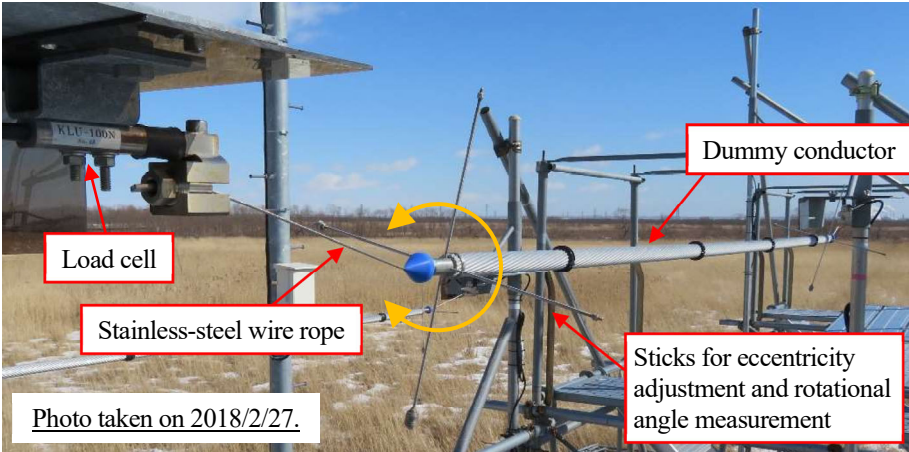
104 aro und a stainless-steel shaft. Because snow accretion develops with the rotation of the conductor, the rotational rigidity of

105 the dummy conductor was adjusted by varying the length and diameter of the stainless-steel wire ropes to simulate the snow

106 accretion characteristics in the middle of the actual lines (Nishihara and Matsumiya, 2012; Nishihara et al., 2017b). The



(a) Simplified observation instruments for snow accretion on conductors on the ground ($h = 4\text{ m}$)



(b) Details of simplified observation instruments for snow accretion on conductor



(c) Insulators for snow accretion observation ($h = 10\text{ m}$)

Figure 3 Simplified instruments for observing snow accretion in various conductors and insulators

107 rotational stiffness of the dummy conductor is determined by the torsional rigidity of the stainless-steel wire ropes, but if
108 there is an eccentricity in the dummy conductor, the rotational stiffness is not linear with respect to the angle. For this reason,
109 a stainless-steel shaft was inserted in the centre of the conductor model so that the dummy conductor was straight, and sticks
110 with small washers were attached to both ends to adjust the eccentricity. The amount of snow accretion was measured
111 directly by load cells installed at both ends, and additionally, the angle of rotation of the dummy conductor and the outer
112 diameter of the snow accretion were measured from the camera images. Similar instruments have also been used to develop
113 a snow accretion simulation method (Ueno et al., 2015). The simplified observation instruments for snow accretion on
114 conductors were installed on the ground ($h = 4,0$ m) and towers ($h = 26, 44$ m) (h : height above ground level) to
115 investigate the effect of slight differences in meteorological conditions on the snow accretion rate. For the observation of
116 insulators shown in Figure 3(c), the differences in snow accretion characteristics depending on the shape and material of
117 insulators were observed using cameras and load cells (Yaji et al., 2017).

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120 3. Countermeasures installed in full-scale lines

121 The amount of snow accretion and dynamic response of the lines due to galloping were compared between lines with
122 different countermeasures. Some of the installed countermeasures are shown in Figure 4 and Table 2. The effects of
123 snow resistance (SR) rings and counterweights were investigated for single conductors, and the effects of
124 current-generated heat (DC: 150 A) on snow accretion development were investigated for two single conductors (Phases D
125 and E). SR rings and counterweights are countermeasures commonly used in Japan to prevent or reduce wet snow accretion
126 (Minyu et al., 1984). The SR rings and counterweights are available in different specifications for various conductor sizes.
127 Excessive snow accretion forms a cylindrical sleeve around the conductor. Cylindrical snow sleeves develop via two
128 different mechanisms: first, the accreted snow slides along the strands of the wire; second, the wire rotates owing to the
129 moment caused by the snow accretion weight. The SR ring is a plastic ring that prevents accumulated snow from sliding
130 along twists on the conductor surface, thus preventing excessive cylindrical snow accretion. A counterweight is an eccentric
131 weight that discourages conductor rotation, thereby preventing excessive cylindrical snow accretion. However, suppressing
132 the conductor rotation might increase the incidence of galloping, owing to the tendency of snow accretion to develop in a
133 single direction (Matsumiya et al., 2019). In this study, the single conductor consisted of the ACSR 240 conductor
134 (aluminium conductor steel-reinforced with a nominal cross-sectional area of 240 mm², diameter: 22.4 mm, torsional
135 rigidity: 68.6 Nm/rad). The SR rings were installed at 500 mm intervals and the counterweights were installed at two
136 positions in the span, 117.4 m and 208.7 m from Tower No. 1. The weight of the counterweight was 11.0 kg, and the length
137 between the conductor and the eccentric weight was 90 mm.

138 Regarding the four-bundled conductor lines, one is a non-countermeasure phase with normal spacers and the other
139 is a countermeasure phase with loose spacers. Line spacers are installed to maintain the spacing of sub-conductors, and
140 normal spacers bundle sub-conductors and typically bear rigid clamps, making it more difficult for the sub-conductors to
141 rotate. Therefore, normal spacers are considered effective in reducing snow accretion to some extent. However, owing to
142 suppression of conductor rotation, galloping is more likely to occur in multi-bundled conductors than in single conductors.
143 Loose spacers have been developed as anti-galloping devices (Inoue et al., 1999; Mitsuzuka and Isozaki, 2007; Matsumiya

et al., 2022b). Loose spacers bear certain rotational and rigid clamps. The rotation angle of the rotational clamps was limited to $\pm 80^\circ$ from the equilibrium position (Ozawa et al., 1995). Loose spacers potentially suppress galloping by ensuring that the snow accretion on the rotatable sub-conductor is smoother (less eccentric) than that on the rigid sub-conductor. In this study, the four-bundled conductor consisted of the ACSR 410 sub-conductors (aluminium conductor steel-reinforced with a nominal cross-sectional area of 410 mm², diameter: 28.5 mm, torsional rigidity: 156.9 Nm/rad) with a spacing of 400 mm. Ten normal spacers were installed in the span, along with eleven loose spacers.

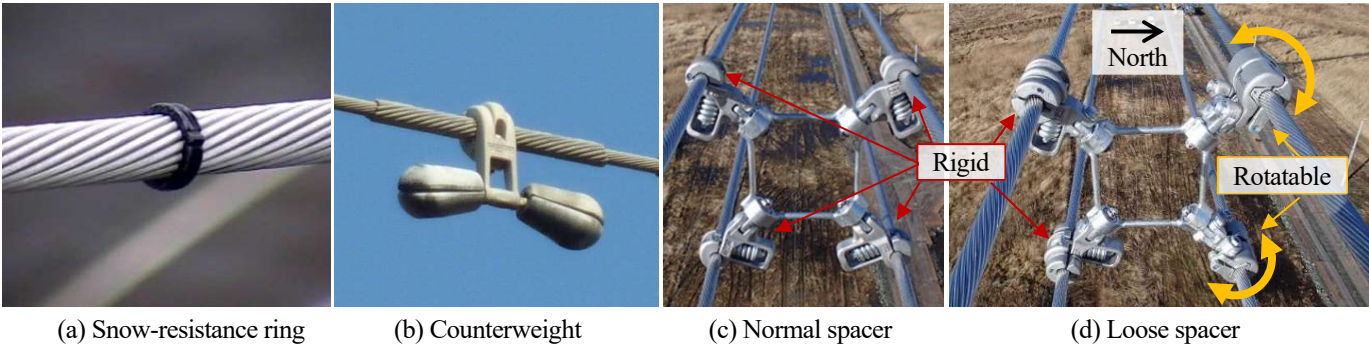


Figure 4 Countermeasures installed in full-scale test lines

Table 2 Specifications of some of the installed countermeasures			
Location	Conditions	Name	Countermeasure
Lower arm ($l = 293$ m, $h = 25$ m at one end (Tower No. 1), $h = 16$ m at the other (Tower No. 3))	Single conductor, ACSR 240 mm ² ($D = 22.4$ mm)	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 ($l = 394$ m, $h = 40$ m at both ends (Towers No. 1 and No. 2))	Four-bundled conductor, ACSR 410 mm ² ($D = 28.5$ mm)	1L	Normal spacers
		2L	Loose spacers

* l : span length, h : height above ground level, D : diameter of conductor

154 4. Observation results for the winter of 2014

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

158 Table 3 shows the maximum amount of snow accretion and the meteorological data statistics for the four cases in
159 which snow accretion occurred in the winter of 2014. Additionally, Figures 5–8 show time series of the meteorological data
160 and amount of snow accretion. Here, precipitation was measured by a tipping bucket rain gauge with a cylindrical
161 windshield, air temperature and relative humidity were measured at 4.0 m above ground level, wind speed and direction
162 were measured at 11.0 m above ground level, and the amount of snow accretion was calculated from the tension of each line
163 by considering the effect of temperature and wind load. All the observed cases of wet snow accretion in 2014 occurred in the
164 moderate wind speed class (3–8 m/s) (Sugimoto et al., 2012) at temperatures slightly above 0 °C and at a relative humidity
165 in the range of 90–100%. Table 3 also includes wet bulb temperatures calculated using average air temperature and average
166 relative humidity (Makkonen, 1989). As the effectiveness of countermeasures differed in the four cases, slight differences in
167 meteorological conditions may affect the effectiveness. The following discussion focuses on the different effects of
168 countermeasures in these cases and discusses the conditions under which the effects of countermeasures are likely to appear.
169 No significant galloping was observed in the cases presented in this study.

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

(a) Maximum amount of snow accretion

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)
1	2014/12/16–17	1.16	1.15	0.97	0.98	1.39	0.63	0.71
2	2015/02/27–28	0.78	0.68	0.26	0.58	0.63	0.80	0.76
3	2015/03/01–02	2.12	1.70	0.40	0.50	0.84	1.91	1.86
4	2015/03/04–05	0.32	0.33	0.24	0.42	0.40	0.21	0.28

* See Table 2 for full descriptions of countermeasures for each phase.

(b) Meteorological data statistics

Case	Snow accretion period	Total precipitation [mm]	Mean air temperature [°C]	Mean relative humidity [%]	Calculated wet bulb temperature [°C]	Mean wind speed [m/s]	Mean wind direction [°]	Mean solar radiation [W/m ²]
1	9:40	29.5	0.20	97.0	0.02	5.0	–27.4	1.2
2	6:40	21.0	0.29	97.4	0.15	5.1	7.8	44.0
3	12:10	52.5	0.33	97.8	0.20	3.7	–27.7	47.8
4	5:50	8.0	0.06	94.3	–0.27	5.9	–27.8	132.2

* Meteorological data statistics are for the period from the onset of snow accretion on any phase to the maximum amount of snow accretion in Phase A.

* Wind direction is the angle relative to the line orthogonal direction (25° azimuth).

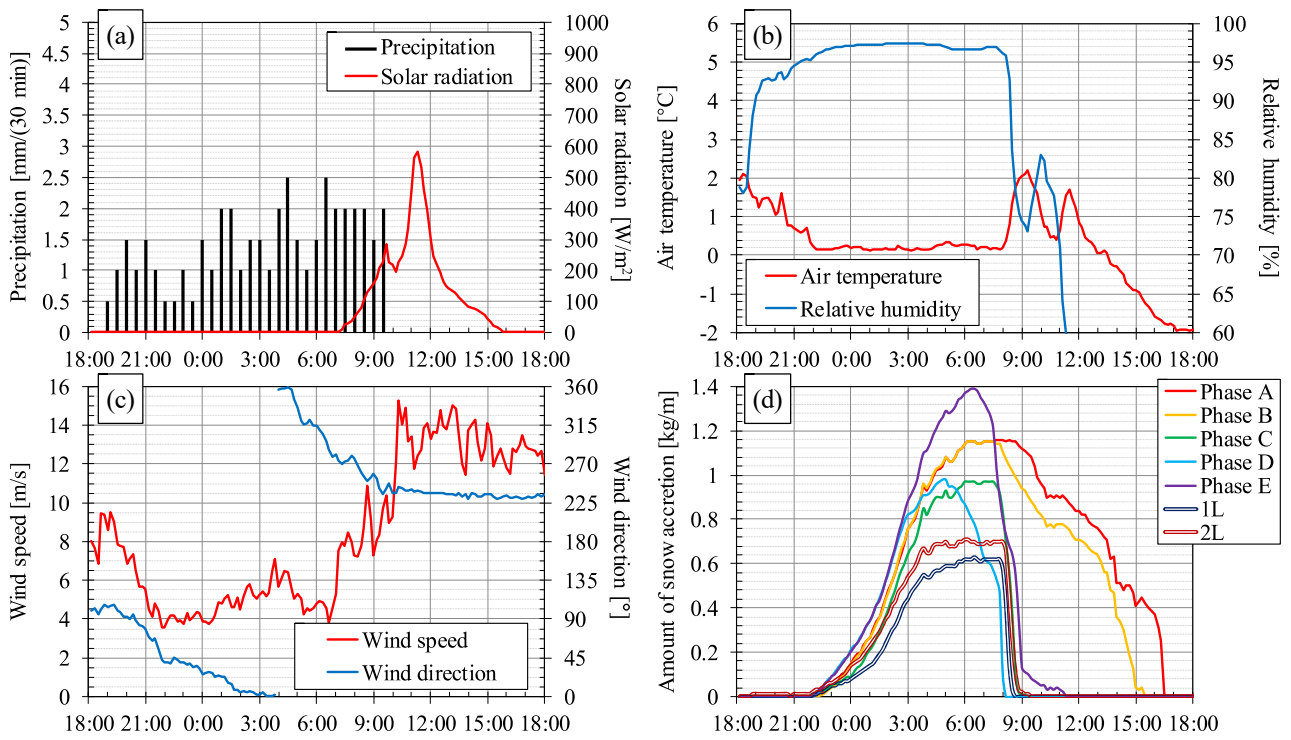


Figure 5 Time series of statistical values of meteorological data and amount of snow accretion for Case 1 (2014/12/16–17)

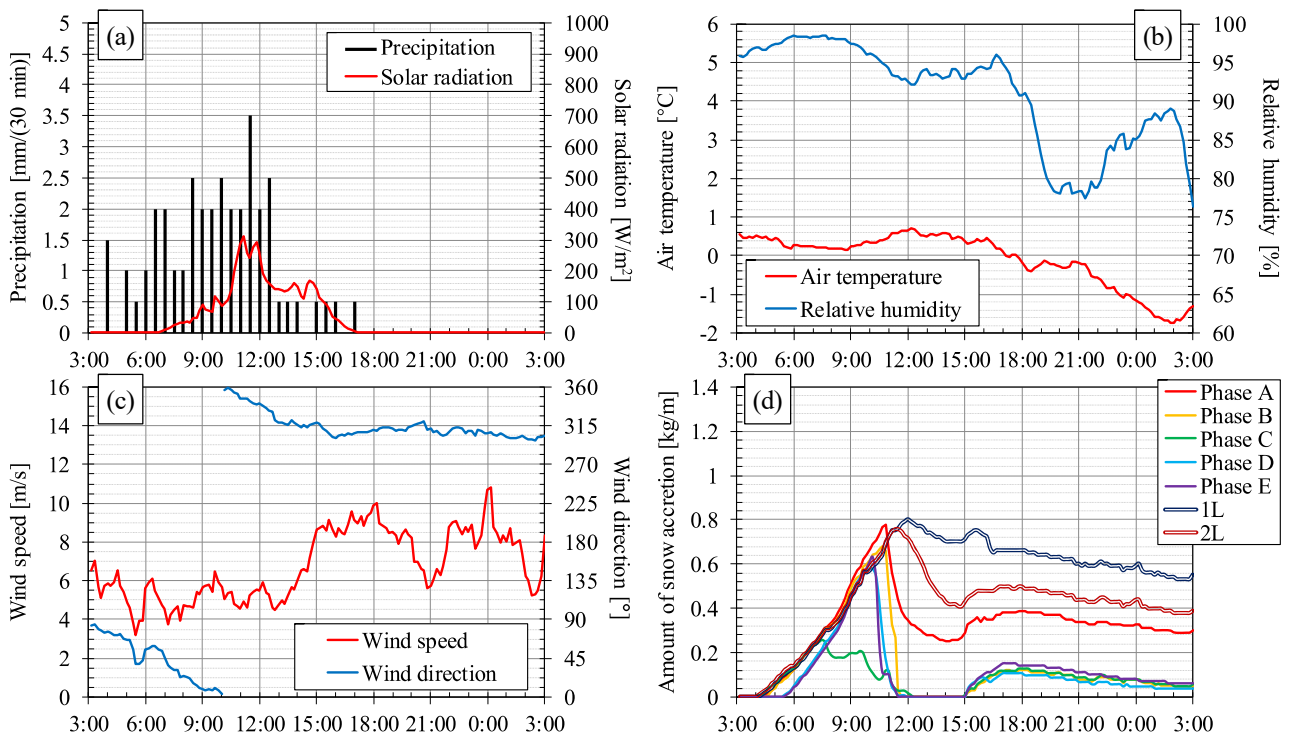


Figure 6 Time series of statistical values of meteorological data and amount of snow accretion for Case 2 (2015/2/27–28)

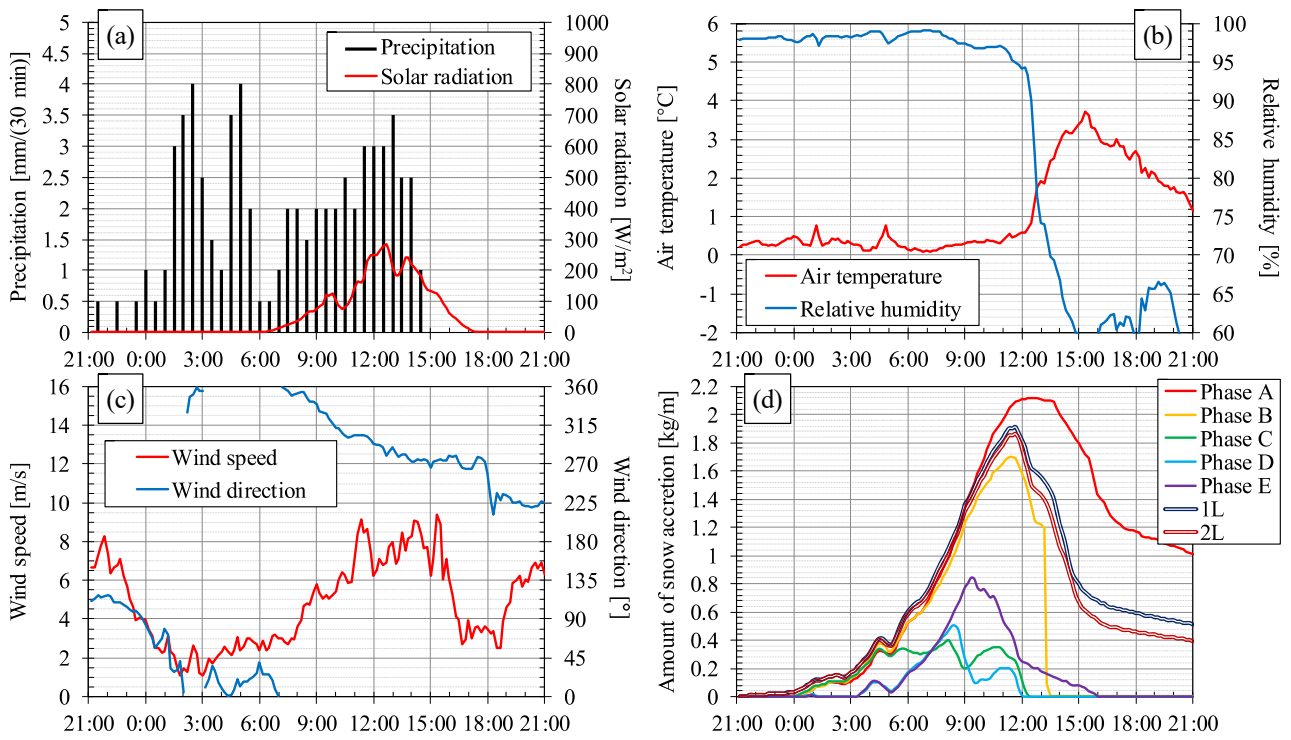


Figure 7 Time series of statistical values of meteorological data and amount of snow accretion for Case 3 (2015/3/1-2)

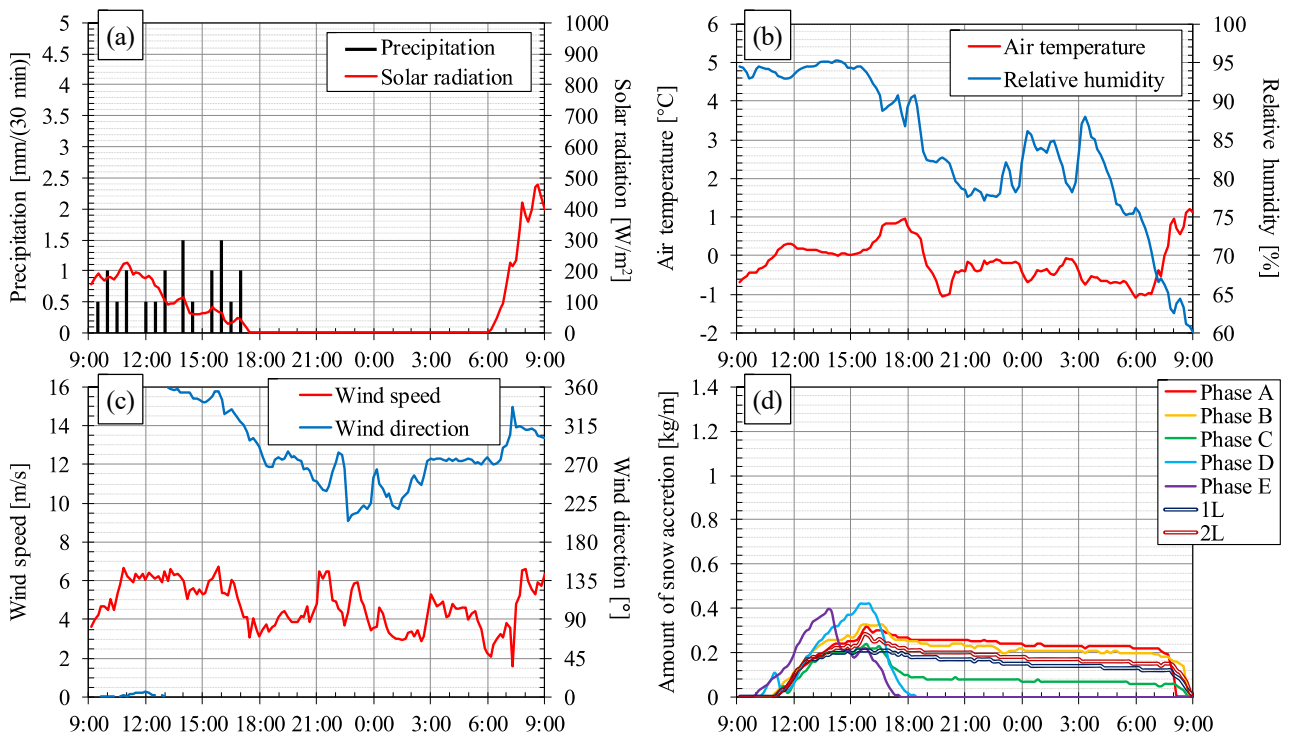


Figure 8 Time series of statistical values of meteorological data and amount of snow accretion for Case 4 (2015/3/4-5)

178 4.1 Snow accretion situation in Case 1 (2014/12/16–17)

179 In Case 1, snow accretion developed in Phase A from 12/16 22:10 to 12/17 7:40, while precipitation continued at
180 temperatures around 0–0.5 °C, as shown in Figure 5. In the average value as shown in Table 3(b), the wet bulb temperature
181 was only slightly above 0° C and there was almost no solar radiation during the snow accretion development period. A
182 comparison of Phases A–C, where the direct current was not passed, shows that the effects of the countermeasures were
183 small in this case. In Phase B, where SR rings were installed, the maximum amount of snow accretion was almost the same
184 as that in Phase A, where no countermeasures were installed. For a more detailed description of the snow accretion
185 situations, Figure 9 shows the snow accretion at a certain time in Case 1, and Figure 10 shows the rotation angle at the
186 quarter and centre of the span. The rotation angle of a single conductor was obtained via image analysis, although some data
187 is missing for periods when the targets could not be recognised in the image. As shown in Figure 9(c), in Phases A and B,
188 although the image was taken from the downwind side, snow covered the wires, suggesting the formation of a cylindrical
189 snow sleeve. As shown in Figure 7, the wire rotated 360° at the centre of the span at approximately 6:00; thus, the
190 cylindrical snow sleeve formed mainly owing to the rotation of the wires. As shown in Figure 9(c) and (d), in Phases C and
191 B, snow covered almost uniformly over the SR ring, suggesting that the effect of the SR ring was weak in these phases.
192 Figure 10 shows that the wire rotated by approximately 180°, even in Phase C, with counterweights. Thus, the snow
193 accretion reduction effect of counterweights was small in this case.

194 Owing to the effect of the current-generated heat (DC: 150 A, 2.7 W/m), the amount of snow accretion was larger
195 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
196 ring is greater with current-generated heat. As shown in Figure 9(d), in Phase E, without SR rings, snow accretion occurred
197 uniformly on the wires, and it is assumed that a cylindrical snow sleeve formed. However, in Phase D, the accreted snow
198 was divided by the SR rings, indicating that the snow has started to shed from the wire.

199 Although the wire diameter difference should be considered when comparing the amount of snow accretion on the
200 four-bundled conductor lines, the amount of snow accretion in 1L with the normal spacers was considerably less than that in
201 single-conductor Phase A. In Figure 9(a), no accreted snow is observed on the downwind side of the sub-conductors,

202 suggesting that the spacers suppressed their rotation, thus reducing the amount of snow accretion. The maximum amount of
 203 snow accretion in 2L with loose spacers, was slightly higher than that in 1L, which could be attributed to the fact that
 204 sub-conductors with the rotatable clamps can rotate.

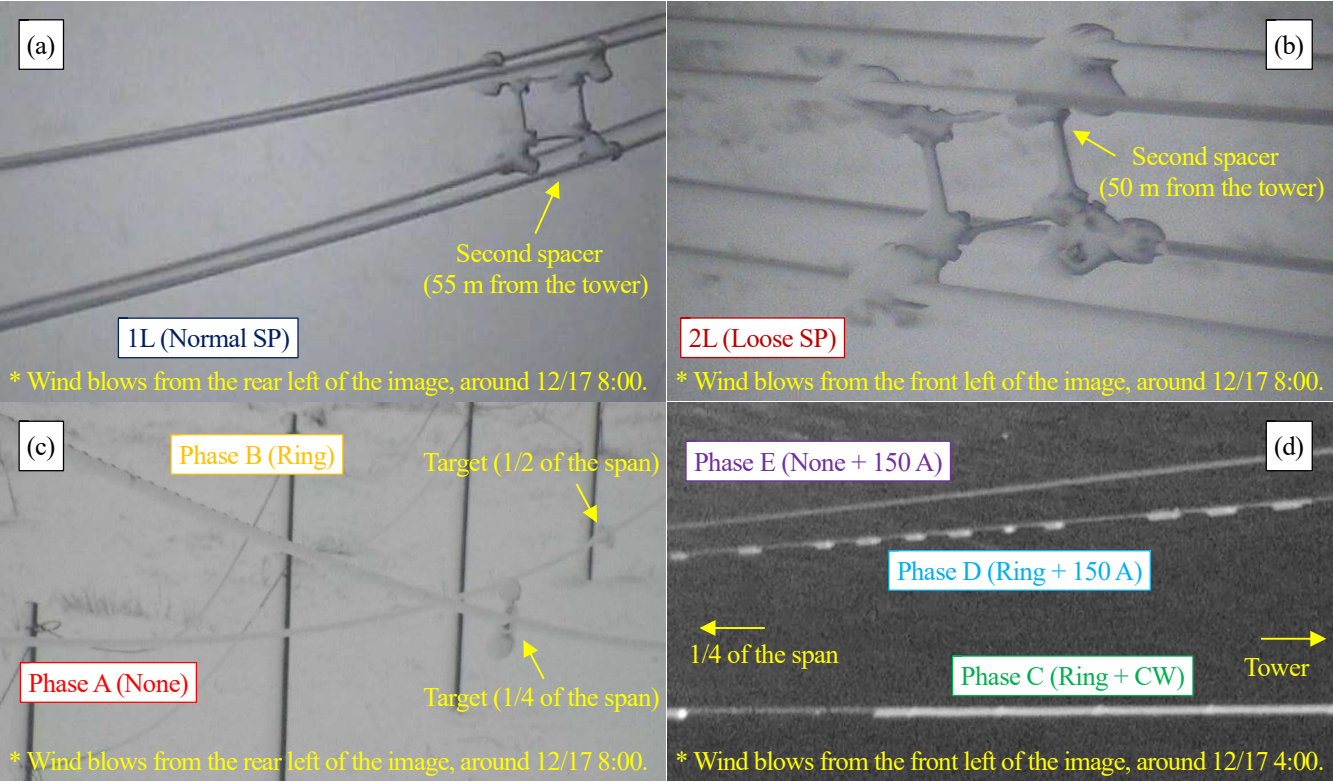


Figure 9 Snow accretion situations on the respective lines (Case 1: 2014/12/16–17)

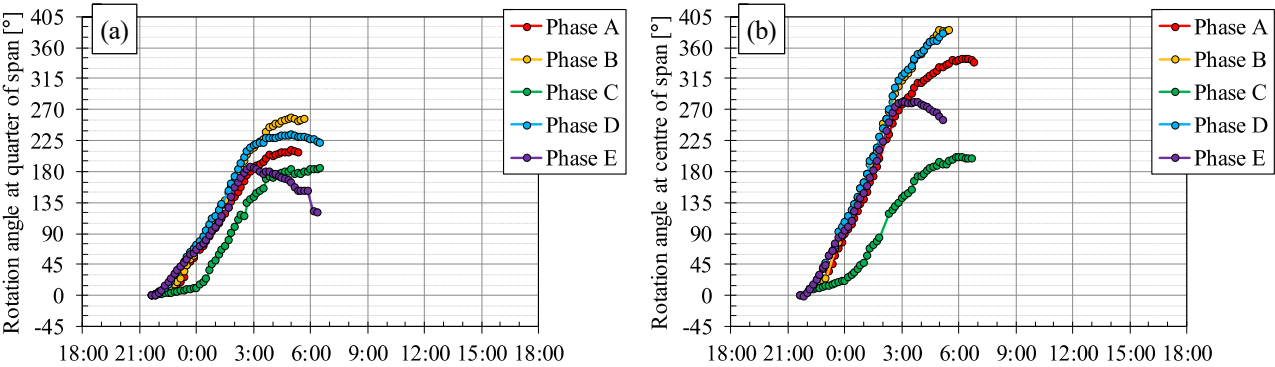


Figure 10 Time series of rotation angle at the quarter and centre of the span for Case 1 (2014/12/16–17)

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207 **4.2 Snow accretion situation in Case 2 (2015/2/27–28)**

208 In Case 2, snow accretion developed in Phase A from 2/27 4:30 to 2/28 10:50, while precipitation continued at temperatures
 209 around 0–0.5 °C, as shown in Figure 6. As shown in Table 3(b), the wet bulb temperature in Case 2 was slightly higher than
 210 that in Case 1, and solar radiation was also stronger. A comparison of Phases A–C, where the direct current was not passed,

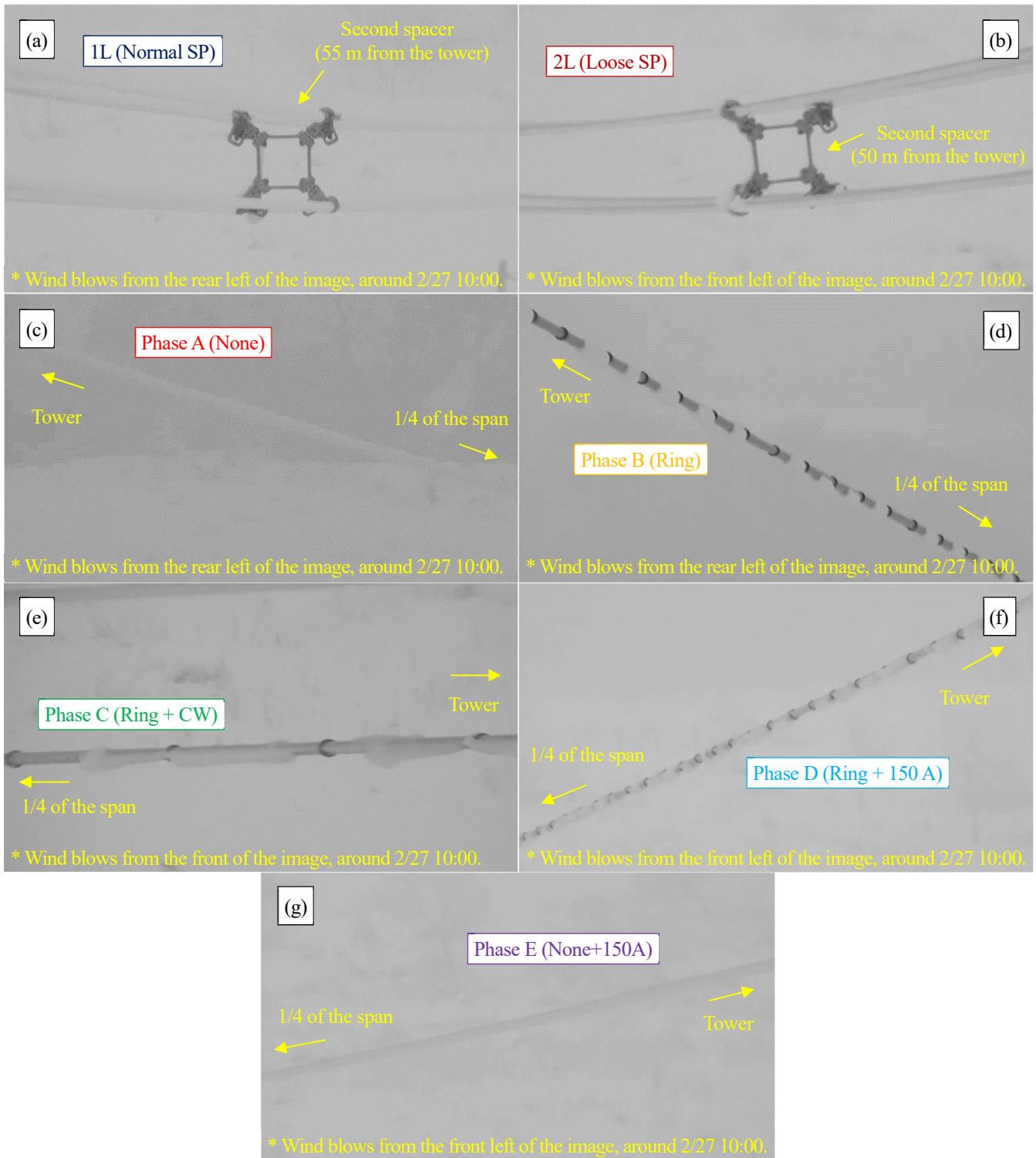


Figure 11 Snow accretion situations on the respective lines (Case 2: 2015/2/27–28)

211 shows that the effect of using the SR rings alone was small but the effect of using both SR rings and counterweights together
 212 was large in this case. Figure 11 shows the snow accretion at a certain time in Case 2, and Figure 12 shows the rotation angle
 213 at the quarter and centre of the span. As shown in Figure 11(c), a cylindrical snow sleeve was formed in Phase A, where no
 214 countermeasures were installed. Furthermore, as shown in Figure 11(d), although it is difficult to fully identify, the fact that

215 the wires in Phase B are visible in some areas suggests that the SR rings could divide the snow accretion. However, Figure
216 12 shows that the wire rotated more in Phase B than in Phase A. It can be assumed that the snow accretion could shed from
217 the wire because of the effect of the SR rings around the tower, where the wire is less likely to rotate due to the proximity of
218 the support point, but a cylindrical snow sleeve could be formed even in Phase B around the centre of the span. In contrast,
219 as shown in Figure 11(e), the snow accretion on the wire in Phase C is less than that in Phases A and B, and snow division
220 by the SR ring is clearly observed. As shown in Figure 12, the rotation angle of the wire is small in this case because of the
221 counterweights. Therefore, the accreted snow could not develop with the wire rotation and could shed with its division by
222 the SR rings.

223 Owing to the effect of the current-generated heat, the amount of snow accretion was not significantly different for
224 Phases D and E than for Phases A and B in this case. As shown in Figure 11(g), a cylindrical snow sleeve was also formed in
225 Phase E. As shown in Figure 11(f), in Phase D, the SR rings could divide the snow accretion to some extent near the tower,
226 but the wire rotation angle in the span was larger than that of Phase E. Therefore, a cylindrical snow sleeve could be formed
227 even in Phase D around the centre of the span due to the rotation of the wire, with similar characteristics as in Phase B.

228 As shown in Figure 11(a), in 1L, although the image was taken from the downwind side, snow covered all
229 sub-conductors, suggesting the formation of a cylindrical snow sleeve, even in the four-bundled conductor lines.
230 Furthermore, the amount of snow accretion of 1L and 2L was almost the same, regardless of the type of line spacer.
231 Therefore, it can be assumed that a cylindrical snow sleeve was formed also in 2L. As the line spacers (normal and loose
232 spacers) prevented the sub-conductors from rotating, accreted wet snow slid along the strands of the wire to form a
233 cylindrical sleeve. There were no SR rings in these four-bundled conductor lines.

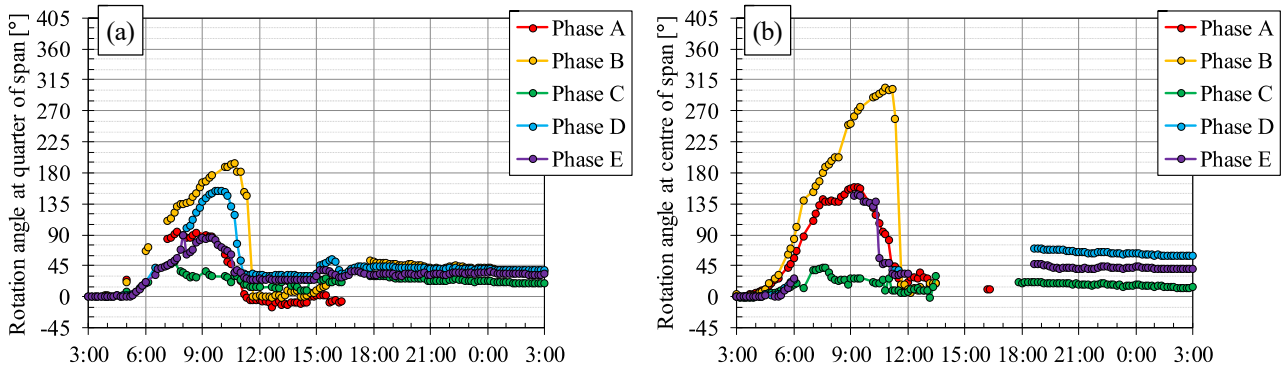


Figure 12 Time series of rotation angle at the quarter and centre of the span for Case 2 (2015/2/27–28)

4.3 Snow accretion situation in Case 3 (2015/3/1–2)

In Case 3, where the most significant snow accretion was observed, snow accretion developed in Phase A from 3/1 0:20 to 12:20, while precipitation continued at temperatures around 0–1 °C, as shown in Figure 6. As shown in Table 3(b), in Case 3, although the wet bulb temperature and mean solar radiation were almost the same as in Case 2, the continuous period of wet snowfall was longer and total precipitation was greater. In Phase A, more than 2 kg/m of snow accreted on the wire, whereas in Phase B the maximum amount of snow accretion was reduced by approximately 20%. Figure 13 shows the snow accretion at a certain time in Case 3, and Figure 14 shows the rotation angle at the quarter and centre of the span. As shown in Figures 13(c) and (d), a cylindrical snow sleeve was formed in Phase A, but in Phase B the accreted snow was divided by the SR rings, and the snow tended to shed from the wire. However, much of the hanging snow remained on the wire. As shown in Figure 14, in Phase A, the amount of snow accretion increased until approximately 12:00, despite a decrease in the wire rotation angle from approximately 8:00. This suggests that in Phase A, the cylindrical snow sleeve developed mainly due to the sliding of the snow along the strands. On the other hand, in Phase B, with the presence of SR rings, the cylindrical snow sleeve was formed mainly because of the rotation of the wire. Moreover, 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 Figure 13(e), the snow accretion on the wire in Phase C is significantly less than that in Phases A and B, and snow division by the SR ring is also observed. Furthermore, as shown in Figure 14, the rotation angle of the wire is small in Phase C; 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

253 D than that in Phases A and B. Furthermore, owing to the effect of the SR rings, the maximum amount of snow accretion in
 254 Phase D was reduced to about 40% of that in Phase E. This result also indicates that the effect of the SR ring is greater with
 255 current-generated heat. As shown in Figure 13(f), while a cylindrical snow sleeve was formed in Phase E, the accreted snow
 256 was divided by the SR rings in Phase D, and it was assumed that some of the accreted snow was shed by the SR rings.
 257 As shown in Figures 13(a) and (b), snow covered all sub-conductors, suggesting that accreted snow developed as a
 258 cylindrical snow sleeve even on the four-bundled conductor lines. Similar to Case 2, as the line spacers prevented the
 259 sub-conductors from rotating, accreted wet snow slid along the strands of the wire to form a cylindrical sleeve. The amount
 260 of snow accretion of 1L and 2L was almost the same, regardless of the type of line spacer.

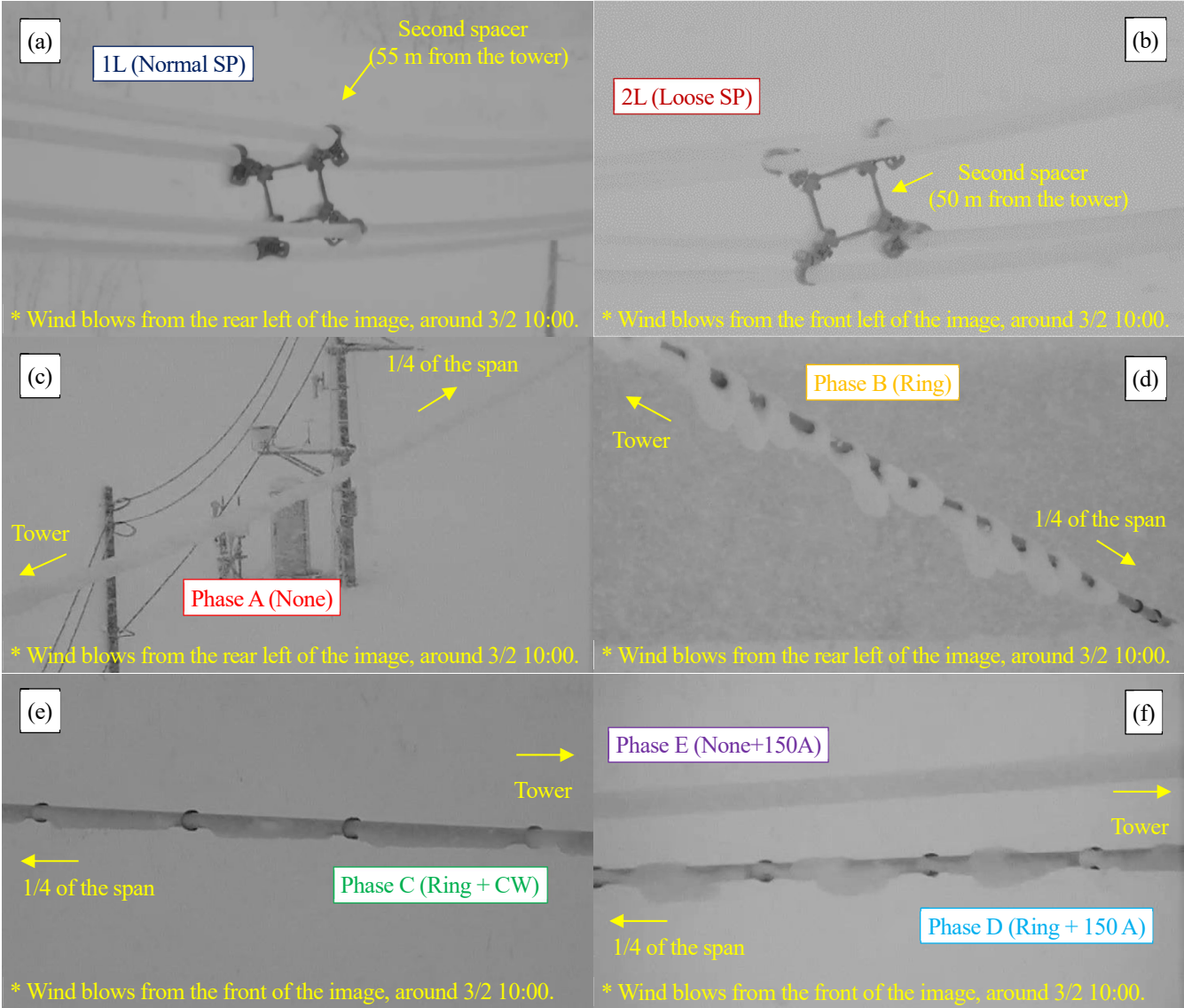


Figure 13 Snow accretion situations on the respective lines (Case 3: 2015/3/1–2)

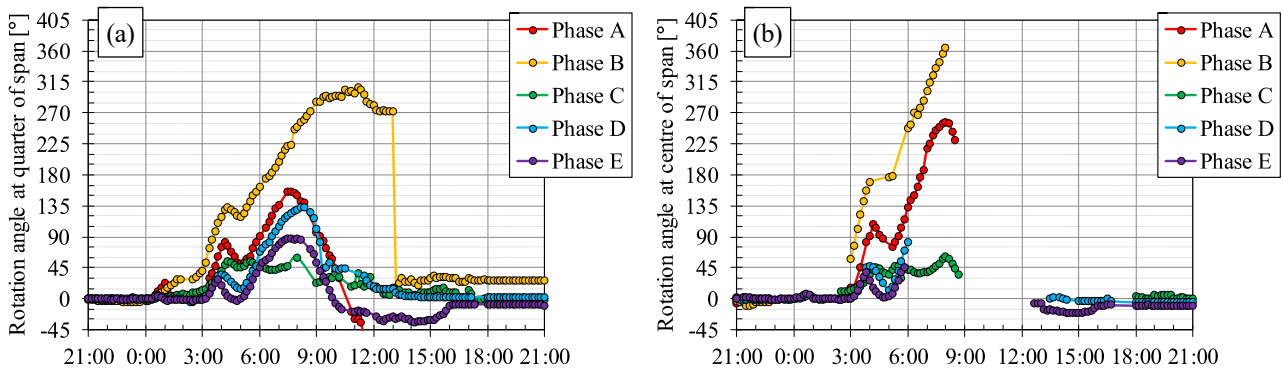


Figure 14 Time series of rotation angle at the quarter and centre of the span for Case 3 (2015/3/1–2)

4.4 Snow accretion situation in Case 4 (2015/3/4–5)

In Case 4, snow accretion developed in Phase A from 3/4 11:10 to 15:50, while precipitation continued at temperatures around 0–0.5 °C, as shown in Figure 8. However, snow accretion started an hour earlier in Phase E, when the temperature was slightly lower, and the maximum amount of snow accretion was larger than in Phase A. As shown in Table 3(b), in Case 4, although mean solar radiation was stronger than that in other cases, the wet bulb temperature was lower. As this is a case of low amount of snow accretion, the difference in the amount of snow accretion due to the countermeasure was small, but the current-generated heat might have affected the conditions under which snow accretion occurred. In the same way that wetter snowfall particles are more likely to attach to the wires, snowfall particles may attach more easily to snow accretion bodies that are wetter due to melting caused by heat generation. The maximum amount of snow accretion in Case 4 is significantly less than those in Cases 1, 2, and 3; therefore, this case is not considered further.

5. Discussion on the effect of countermeasures

As indicated in Section 4, the effectiveness of the countermeasures differed between the wet snow accretion cases investigated in this study. In Case 1, the accreted snow hardly slid along the strands of the wire, whereas in Cases 2 and 3, the accreted snow slid easily. The sliding behaviour of the accreted snow is dependent on its liquid water content. In other words, accreted snow slides more easily if it is subjected to a large amount of heat from the outside and melts to some extent. The heat transfer from air to the snow is greater when the temperature, humidity, and wind speed are higher. Wet-bulb temperature, which takes into account the relationship of temperature and humidity, is an indicator of the melting conditions

280 of snow accretion. Furthermore, solar radiation also influences snow melting and sliding. In Cases 2 and 3, the melting of
281 the accreted snow due to heat transfer from air and the effect of solar radiation was greater than that in Case 1; the snow
282 easily slid along the strands of the wire and induced the formation of a cylindrical snow sleeve on the four-bundled
283 conductor without SR rings. In contrast, in cases where the snow is easily slidable, the effect of the SR ring is more likely to
284 occur, and if the rotation of the wire is also suppressed by counterweights, a significant countermeasure effect against snow
285 accretion is achieved. Similarly, as shown in Cases 1 and 3, more heat generated by the electric current facilitated the sliding
286 of the snow along the strand, making the SR rings more effective. It was also found that snowfall particles are somewhat
287 more likely to be attached when the snow accretion body has large liquid water content, and heat generated by the electric
288 current sometimes facilitates snow accretion in the absence of countermeasures.

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

294

295 **6. Conclusions**

296 The Kushiro test line, a full-scale test facility, was constructed for field observations of wet snow accretion on conductors
297 and insulators as well as galloping in overhead lines. Herein, the features of the facilities and typical observation results for
298 wet snow accretion on conductors are presented. Furthermore, the effects of countermeasures on reducing the amount of
299 snow accretion are discussed based on observations.

300 In the case of single conductors without countermeasures, snow accretion develops as a cylindrical sleeve with
301 wire rotation. Therefore, countermeasures to prevent wire rotation, such as counterweights, are effective. However, wet
302 snow sometimes exhibits snow accretion that occurs as cylindrical sleeves, even in four-bundled conductors where line
303 spacers prevented the wire from rotating. This indicates that the accreted wet snow slides along the strands of the wire to

304 form a cylindrical sleeve. Melting of the accreted snow, caused by heat transfer from air and the effect of solar radiation,
305 makes it easy for the accreted snow to slide along the strand on the wire surface and induces the formation of a cylindrical
306 snow sleeve without SR rings. However, snow tends to shed from the wire in the presence of SR rings. Moreover, the heat
307 generated by the electric current in the conductor accelerates this effect. Furthermore, the SR rings are more likely to result
308 in this snow shedding if counterweights suppress wire rotation.

309 The snow accretion cases presented in this study are distinctive events observed at the Kushiro test line. As the
310 cases described here might be unusual, further analyses should include other cases. However, these unusual cases have
311 allowed for the identification of when SR rings are more likely to be effective. Furthermore, to clarify the differences in the
312 countermeasure effects between the metrological conditions in detail, the heat balance around the accreted snow should be
313 modelled (Poots, 1996; Farzaneh, 2008) and each effect should be quantitatively evaluated for typical wet snow cases. As
314 the effects of countermeasures also depend on the physical properties of accreted snow, such as density and liquid water
315 content (Ueno et al., 2015), the evaluation models of these properties will be developed and validated by experiments in a
316 low-temperature wind tunnel (Abe and Kosugi, 2019; Yamamoto et al., 2020). Observations at the Kushiro test line will be
317 continued to clarify the mechanism of snow damage, including galloping, and to verify the overall effectiveness of the
318 countermeasures adopted.

319

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