The Physics of Wet Snow Accreted on an Overhead Wire

Literature review report presented to Électricité de France,
within the framework of a CIGELE/McGill collaborative project

by

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1. Introduction

Snow accretion on overhead conductors and ground wires can lead to a number of issues related to safety, mechanical reliability and serviceability. Large dynamic overloads can cause the fatigue and eventual breakage of wires and collapse of support structures. Unequal sags and wire oscillations due to the shedding of the accreted snow can cause flashovers between phases. Galloping motion of the wires due to aerodynamic instability of the wire-snow profile may also lead to inter-phase flashovers and wear of fittings and members (Sakamoto 2000). Wet snow accretions, as reported by Colbeck & Ackley (1982), are particularly troublesome because a large mass accumulation can occur in only a few hours.

The objective of this report is to assess the current state of knowledge of the mechanical properties of wet snow when it is accumulated on an overhead wire. This review is the first step towards a study of the dynamic effects of wet snow shedding from an overhead wire. The present study, which is part of the requirements of a Master of Engineering thesis, is sponsored by Électricité de France (EDF), within the framework of its partnership with CIGELE, and is co-supervised by Professor Ghyslaine McClure of McGill University and Professor Masoud Farzaneh of Université du Québec à Chicoutimi (UQAC – CIGELE).

A lot of the useful literature on the physics of accreted wet snow comes from authors whose field of research concerns modeling the accretion mechanism of wet snow on an overhead wire. The main objective of these models is to predict the amount of snow overload based on the meteorological parameters at the time of accretion. Concerning these accretion models, most contributions have been made by Wakahama, Poots, Skelton, Sakamoto and Admirat.

Colbeck and Denoth are also major contributors to the understanding of the physics of wet snow. Their research efforts dealt with the evolution of the microstructure of wet snow and the study of its liquid water content.

Various aspects of the physics of wet snow on an overhead wire are described in this review. They have been grouped in four chapters. Wet snow accretion on a wire is described in a general way in chapter 2. A more thorough description of the nature of wet snow and its regimes of water saturation is found in chapter 3. *In situ* and laboratory observations are reported in chapter 4. Chapter 5 addresses the subject of wet snow shedding from a wire.

The last chapter of this review deals with dry snow mechanics. Since there are no records of actual material testing on wet snow samples, the only source of data that could be used to estimate the mechanical properties of wet snow - at least in a qualitative way - comes from this related field of research.

In this report, the term “overhead wire” is used to designate a stranded conductor or ground wire (regular or optical) used in electric overhead transmission lines.

2. Snow accretions on overhead wires

2.1 Types of snow accretions

2.1.1 Dry snow accretions

In practice, two types of snow accretions can be distinguished: wet and dry. Dry snow accretions occur at sub-zero air temperatures, and are limited to very low wind speeds (typically less than 2 m/s); their densities are low and rarely exceed 0.1 g/cm³; their adhesive force is also very low and they rarely give rise to extreme loads. However, a complete cylindrical sleeve may form and shed spontaneously along its entire span, leading to a pronounced rebound (Sakamoto 2000).

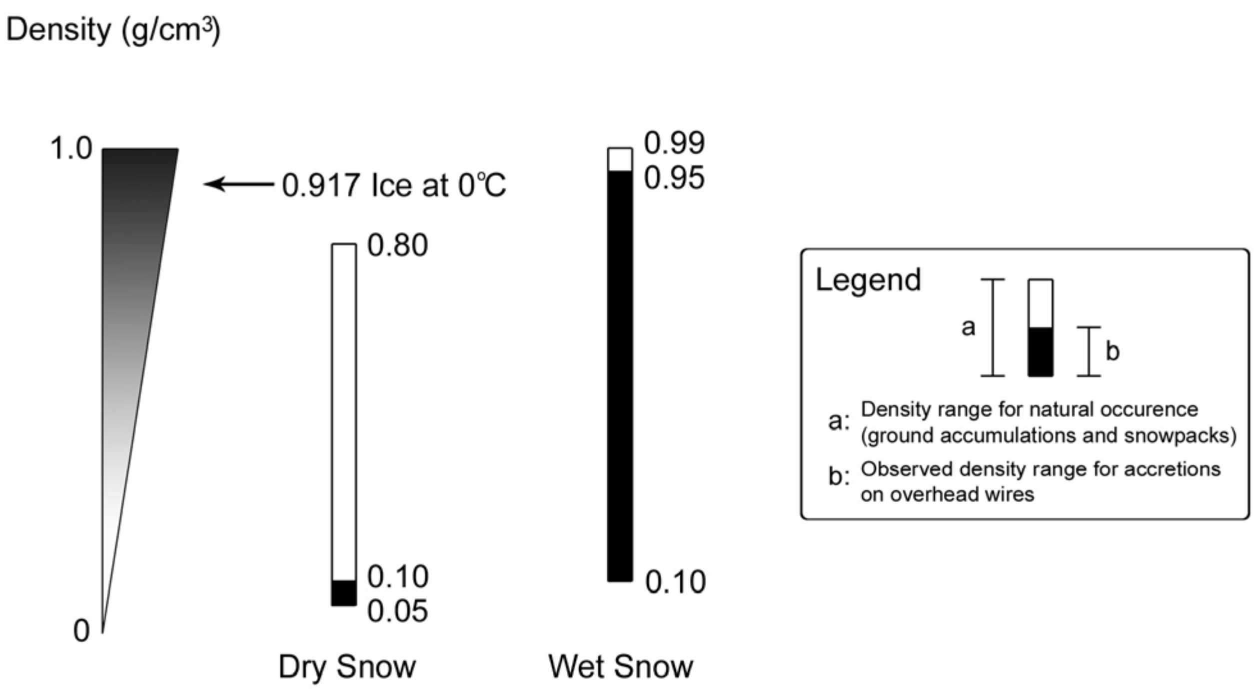

Fig.1 Wet and dry snow density comparison

2.1.2 Wet snow accretions

Wet snow accretions typically occur at air temperatures slightly above the freezing point. They are more severe than dry snow accretions and their density (see Fig.1) spans a much wider range (0.10 to 0.95g/cm³). They may also form into a complete cylindrical sleeve, but their greater adhesive strength makes them unlikely to shed from wind loads alone, causing heavy overloads to overhead wires and structures.

2.2 Growth of wet snow accretions

As in the case of rime ice accretions, wind-borne wet snow particles adhere to the windward side of overhead wires. The accreted mass grows into the wind, causing an eccentric load on the wire (Poots 1996). Two modes of accretion have been observed along the span of an overhead wire: axial growth and cylindrical sleeve growth (Fig.2).

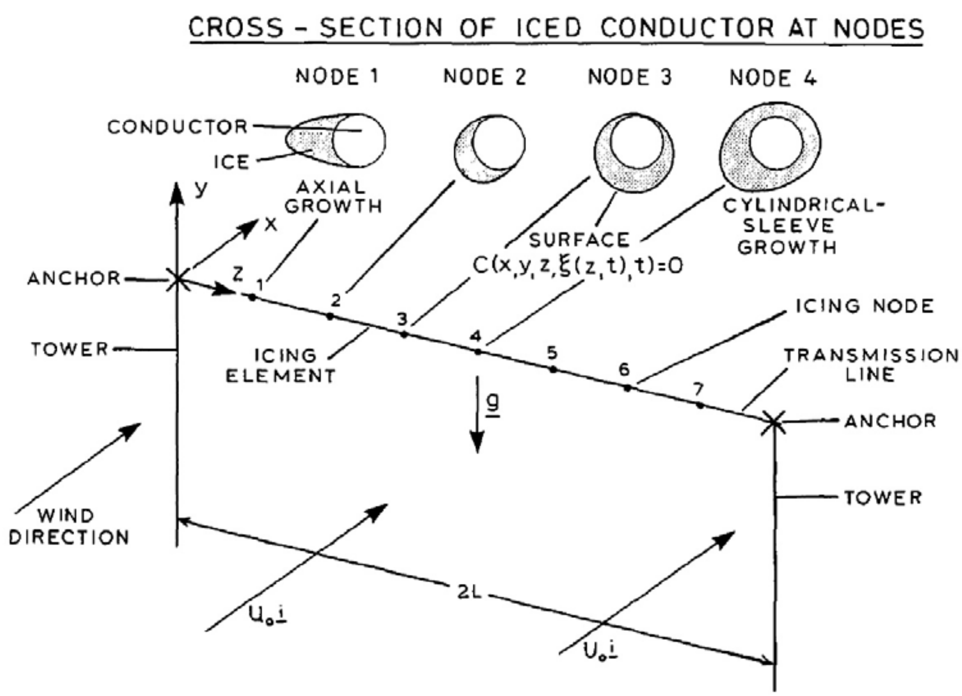

Fig.2 Variation of snow profile along the span of an overhead wire
(from Skelton & Poots 1991)

2.2.1 Axial growth (Fig.3)

Axial growth occurs on the windward side when rotation is prevented, i.e. at the towers where the wire is anchored. In this case, the snow accretion simply grows outwards into the wind.

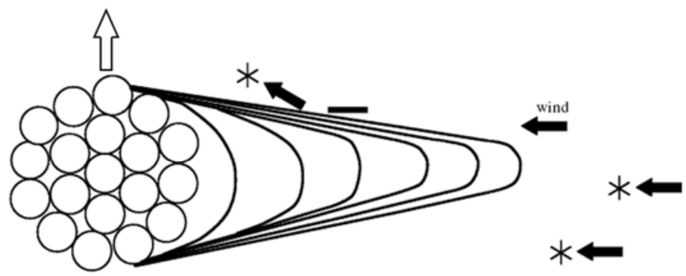

Fig.3 Axial growth on a stranded wire
(from Sakamoto 2000)

2.2.2 Cylindrical sleeve growth (Fig.4)

Using wind tunnel experiments, Wakahama (1979) was the first to demonstrate how the wind causes an accretion to rotate and build uniformly around a wire.

Since an overhead wire has finite torsional stiffness and finite span, it rotates about its axis under the effect of the eccentric snow loading: at its mid-span the wire can undergo more than one revolution and the accretion becomes a cylindrical sleeve. As the wire goes through several revolutions its diameter is further increased.

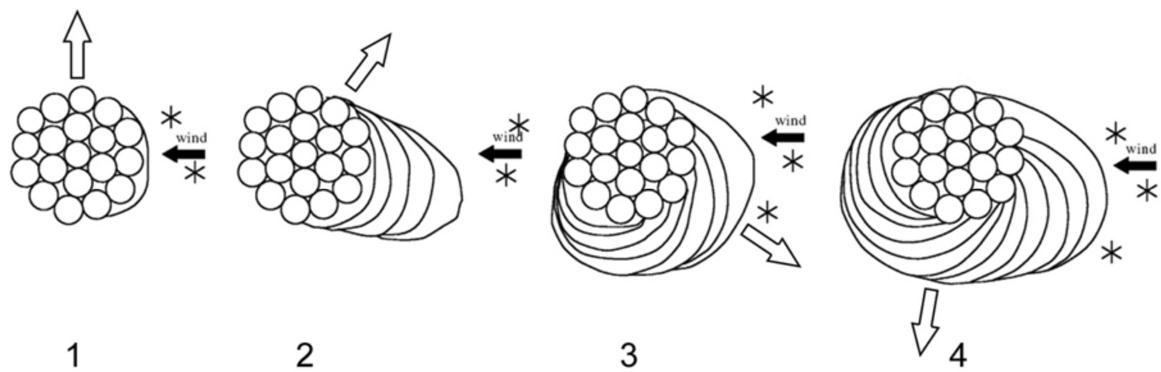

Fig.4 Cylindrical sleeve formation. The white arrows indicate wire rotation. (from Sakamoto 2000)

This accretion mode is called “cylindrical sleeve growth”. In the case of a wire having low torsional stiffness (such as an overhead ground wire or a single conductor phase – as opposed to a bundle of two or more conductors) a cylindrical sleeve may almost cover the entire span (Poots 1996). Once a full cylindrical sleeve has formed, it is very unlikely to shed from wind loads alone.

2.3 Effects of the wind

Wind is responsible for packing the accreting snow grains to a high density mass: the impacting forces of snow particles and the wind drag contribute to densify the accretion. The snow densities accreted on an overhead wire are normally much higher than the densities of snow on the ground during the same event. After the snowfall the accretion is further compacted by the wind drag and gravity; both effects are balanced by the increased tension in the wire. The nature of wet snow makes it easily compressible: wind has a considerable effect on the compaction of wet snow sleeves, especially at higher liquid water content values (Colbeck & Ackley 1982).

The apparent diameter of an overhead wire increases as a snow sleeve grows. This increase in cable weight is taken by the support structure and may lead to its collapse if the load exceeds its capacity.

Wind-on-cable loads are also amplified by the increase in exposed diameter. Sustained quasi-steady winds and/or dynamic gusts can cause significant lateral loads on the supporting towers.

Conductor galloping is another kind of dynamic load that can be induced by wind on the accreted snow profile.

3. Wet snow metamorphism in the pendular and funicular regimes

3.1 The physics of wet snow

“During wet snow accretion on an overhead wire, occurring at positive air temperatures, the liquid water content (LWC) of the snow matrix controls the strength of the capillary forces and promotes contact between ice granules leading to ice bonding.” (Poots 1996)

The previous quote is a very elegant and concise summary of the origin of wet snow’s cohesive strength when it is accreted on an overhead wire. In order to appreciate it fully one needs to have a better understanding of what wet snow is, how it evolves under environmental factors and how it is described and quantified.

Wet snow particles are an agglomeration of snowflakes and a mixture of ice, liquid water and air. The physical properties of wet snow are extremely variable. Different ratios of ice, water and air produce microstructures with different densities and liquid water content values. This, in turn, leads to a wide range of adhesive properties and strengths (Poots 1996). Moreover, the microstructure is continuously evolving and it undergoes metamorphism with changes in liquid water content, temperature and/or temperature gradient (Colbeck 1982, 1997).

3.2 The liquid water content of wet snow

The key variables when describing wet snow accretions are: density, snow overload (mass per meter of wire length) and liquid water content (LWC).

Most of the documentation on snow metamorphism and snow accretion on overhead wires is consistent; however, the LWC parameter is expressed differently from one author to the next, which makes reading articles from different authors sometimes confusing. There is no standard definition for the LWC of wet snow accreted on an overhead wire, , but there is a trend that goes against the convention established to describe the LWC of snow accumulated on the ground.

In 1985, the International Commission on Snow and Ice established the Working Group on Snow Classification to update the system for classifying snow on the ground. The group, chaired by S.C. Colbeck, defined the LWC of snow as the percentage of liquid water per volume of snow. This definition became an international standard to describe the LWC of snow layers on the ground, and is currently used by researchers studying mountain snowpacks and avalanches.

Liquid water content **General symbol: θ**

Measurements of liquid water content or wetness are expressed as a percentage by volume, which usually requires a separate measurement of density. Several methods are in use today for field measurements to determine liquid water content: hot (melting) and cold (freezing) calorimetry, dilution and dielectric measurements. A general classification of liquid water content is given in Table 4.

Liquid water is only mobile if the irreducible water content is exceeded. The irreducible water content is about 3% by volume and depends significantly on snow texture, grain size and grain shape. This is the water that can be held by surface forces against the pull of gravity.

(from Colbeck *et al.* 1990)

The above description is referred in this review as "%LWC by volume". It does not give a complete representation of the level of water saturation of snow. Denoth (1982) has a better way to express the extent to which snow is saturated with liquid water: he defines saturation as the ratio of the LWC of snow (% volume) to its porosity. In other words, Denoth defines the amount of water saturation as the extent (%) to which liquid water fills the available pore space in the snow matrix.

Wakahama (1977, 1979), Poots (1996), Admirat (1986, 1988, 1990) and Sakamoto (2000, 2005) all express the LWC as the mass of liquid water divided by the total mass of wet snow, in % (% LWC by mass).

LWC can also be defined as the mass of water per unit volume of solid (g/m^3). In the literature this definition is rarely used to describe the LWC of wet snow.

3.3 The regimes of liquid water saturation

Wet snow has two basic modes, or regimes, of liquid water saturation: the pendular regime and the funicular one. At low LWC values (Fig.5a), snow is said to be in the pendular regime and air is continuous throughout the pore space. The funicular regime (Fig.5b) occurs at higher LWC values, when water becomes continuous throughout the pore space.

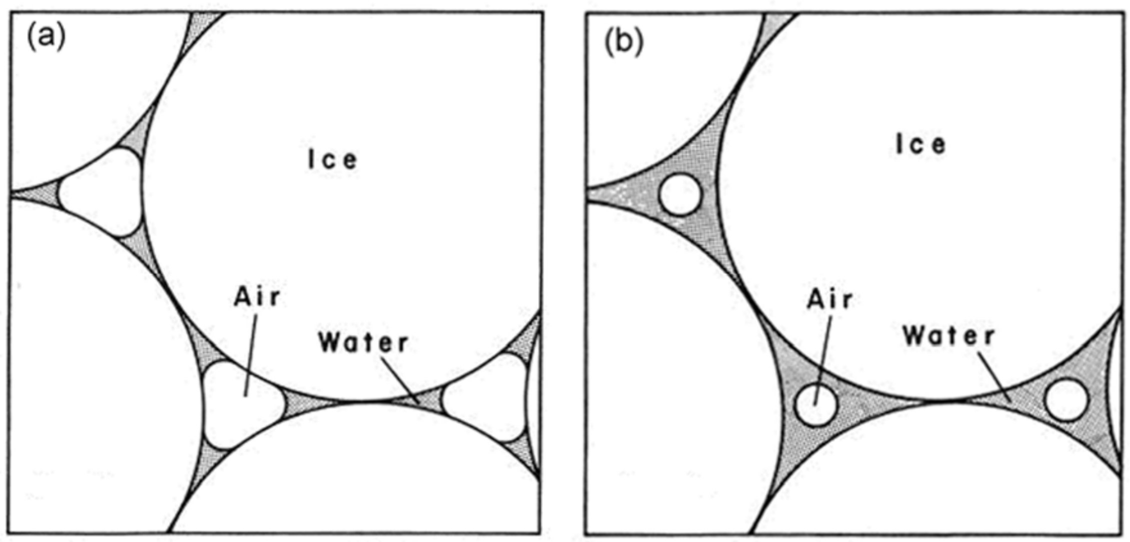

Fig. 5 Wet snow in the a) Pendular and b) Funicular regimes
(from Colbeck 1973)

Using an ideal model of uniform spherical grains, Colbeck (1973) estimated the transition between the pendular and funicular regimes at a liquid saturation of about 14%. Denoth (1980) observed experimentally that the transition between the two regimes occurs in the range of 11-15% of liquid saturation. This roughly corresponds to a LWC of about 7% by volume, or about 20% by mass.

It should be stressed here that the liquid saturation and LWC are two different parameters. Although the LWC measure may be used to calculate the amount of liquid saturation, they are not directly proportional. LWC is used to evaluate the amount of liquid water in wet snow because it is readily measured using a simple freezing calorimeter. However, it does not truly represent the amount of liquid saturation of the snow matrix.

At air temperatures above freezing the LWC of wet snow on a wire increases with time due to heat transfer from the moving warm air (and Joule effect if the cable carries a current). Since wet snow is often accompanied by rain and/or freezing rain, liquid precipitations may also increase the LWC of wet snow sleeves.

3.3.1 Wet snow metamorphism in the pendular regime

At low LWC (up to approximately 20% by mass or 7% by volume), wet snow is said to be in the pendular regime. Liquid water is contained in menisci held between individual particles and air is continuous throughout the pore space. Typical field measurements for the LWC in this “unsaturated” regime range between 3-5% by volume (Colbeck 1979).

As wet snow adheres to an overhead wire, the large packing forces exerted by the wind bring the ice particles into close contact. By capillarity, the liquid water contained in the snow matrix facilitates contact between individual ice grains and promotes heat transfer (Colbeck & Ackley 1982).

In wet snow, the ice grains attempt to reach a state of minimum surface-free energy: this means that individual grains tend to cluster, get rounder and fewer (larger ones grow at the expense of smaller ones) (Colbeck 1982, 1995). This metamorphism is driven by conduction heat flow resulting from small temperature differences between individual grains. In the case of accretion on an overhead wire, the metamorphism begins in the atmosphere where wet snow flakes fall through air at a slightly positive temperature. Once they have accreted on the wire, snowflakes are subjected to wind loads and thermal exchanges with the environment and with the wire. In such conditions, Admirat and

Sakamoto (1988) suggest that the complete rounding and clustering process occurs within a few seconds.

Grain clusters (Fig.6) develop as their boundaries evolve: large grain boundaries are more stable thermodynamically. However, grain boundaries tend to melt if subjected to large normal compressive loads. The density of each grain cluster averages 0.5-0.6g/cm^3, but this does not reflect the density on the macroscopic scale: the bulk density of the snow depends on how closely packed grain clusters are with respect to one another. In fact, the density is much lower if there are large air-filled voids among the grain clusters. On the other hand, the overall snow strength depends on the number of grain boundaries found in a given volume of snow. A higher number of grain boundaries means that there are more interconnecting links between grain clusters, and hence greater overall strength. As the density of the wet snow increases above approximately 0.6g/cm^3 the grain clusters are replaced by a continuous network of interconnected grains and, as a result, snow strength is further increased (Colbeck 1982).

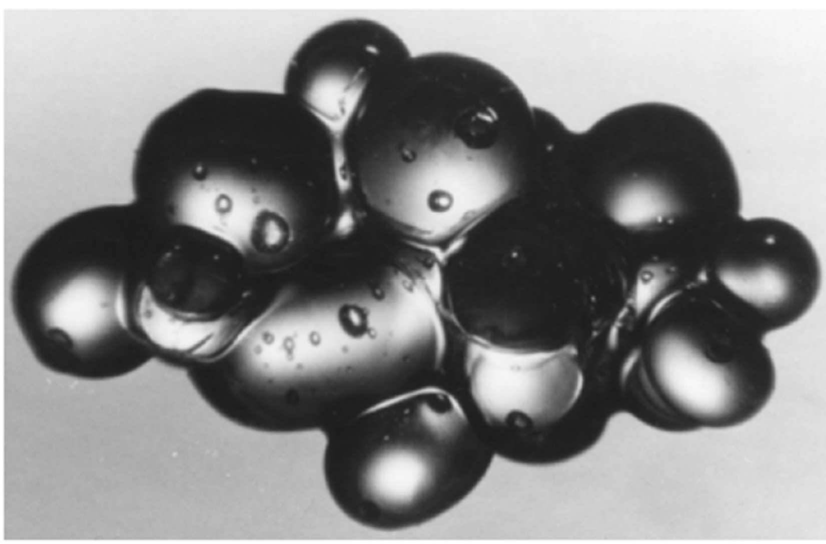

Fig.6 Grain cluster in the pendular regime. These clusters arise naturally because they minimize the surface free energy. (from Colbeck 1997)

“In the snow cover on the ground these higher densities take months to achieve unless many meters of wet snow accumulation occur. On power lines, in the presence of high winds, the forces are sufficient to cause high accretion densities and the large specific grain boundary areas. Thus only a few hours is required to develop high strength, simultaneously with grain growth and grain rounding, in wet snow on power lines.” (Colbeck & Ackley 1982)

As mentioned above, liquid water is contained in the menisci held by individual particles, in internal veins and external fillets (Fig.7). Veins occur at triple grain junctions and liquid fillets are found along grain boundaries (Colbeck 1997).

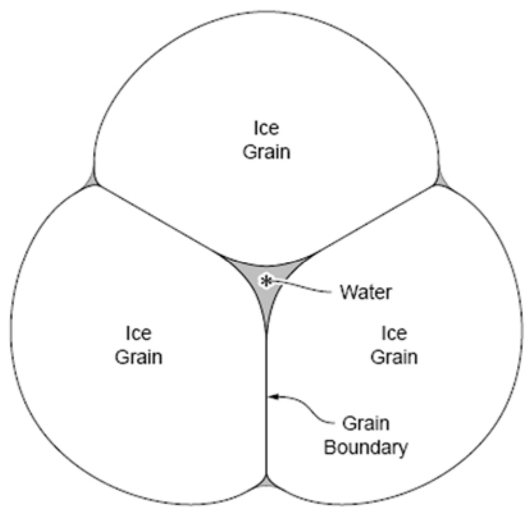

Fig.7 Three-grain cluster. Liquid water is held in the crevices between two grains, the veins between three grains and at the junctions of four grains.
(from Colbeck 1997)

Veins and fillets are quickly frozen if the temperature of the snow matrix drops below 0°C and they are not necessarily reformed upon melting (Fig.8). This explains the significant increase in the strength of wet snow sleeves that are subjected to overnight freezing, as reported by Sakamoto (2000).

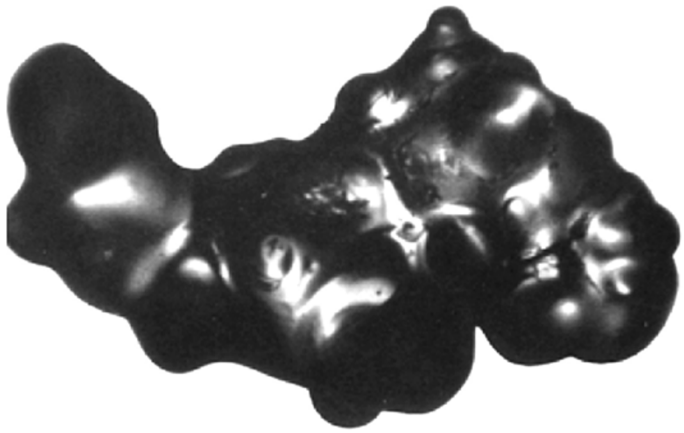

Fig.8 Amorphous grain cluster produced by melt-freeze cycles
(from Colbeck 1997)

Wet snow is well bonded in the pendular regime: individual ice grains join in groups of two or more and are tightly bonded by ice-to-ice contacts. Colbeck & Ackley (1982) demonstrated that coherent forces (ice bonding) through metamorphosis are necessary to wet snow sleeve formation. Capillary forces alone cannot account for holding the sleeves together because of their low shear strength (but high tensile strength). Wet snow sleeves, however, exhibit considerable shear strength by resisting both gravity and wind forces against the overhead wire. Therefore solid-solid particle bonding must occur, even in the absence of subfreezing external conditions.

Rare meteorological conditions can produce low LWC values (<20% by mass). During such exceptional events, unrestricted development of snow sleeves may occur, leading to serious overloads and damages to overhead wires and structures (Poots 1996). In such circumstances, Grenier et al. (1986) suggest that Joule heating of the conductor be used to promote snow melting and increase the LWC of the snow matrix. Increasing the LWC in the funicular regime (LWC>20% by mass) reduces the cohesive strength of the snow matrix and can lead to shedding of the accretion.

3.3.2 Wet snow metamorphism in the funicular regime

At high LWC (20%-40% by volume), liquid water is continuous throughout the pore space, and air is trapped in the form of bubbles. This “slushy” regime can only occur if the water contained in the snow is prevented from draining. In this regime, the ice crystals are relatively large and the snow matrix acts almost like a fluid (Fig.9); slushy snow has a low bonding strength because the crystals are fewer, rounded and weakly held together (Colbeck 1982, 1997).

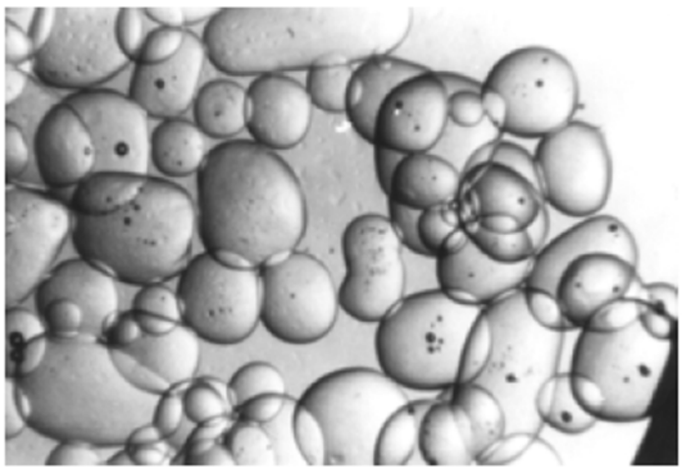

Fig.9 Wet snow grains in the funicular regime
(from Colbeck 1997)

In the funicular regime, ice bonds disappear as LWC increases. As the number of ice bonds decreases, coherent forces are reduced to capillary bonds which are strong in tension, but weak in shear. Natural self-shedding of wet snow sleeves on overhead wires occurs in the funicular regime when the gravitational and aerodynamic loads exceed the internal forces holding the sleeves together and on the wire (Grenier et al 1986, Poots 1996).

A close parallel can be made between wet snow shedding from an overhead wire and a specific type of avalanche: it is thought that water-saturated snow layers (in the funicular regime) are responsible for causing wet snow avalanches (Colbeck 1986).

4. Field and laboratory observations

Wet snow accretions are difficult to study. They are rare and often limited to specific locations with special topographic or microclimatic conditions. Also, field observations are typically made several hours or even days following a storm.

Compared to other types of icing accretion, natural wet snow accumulated on a wire is difficult to observe since it might shed in a relatively short time or change its LWC and strength rapidly. (Sakamoto, 2000)

4.1 Field observations in France, Japan and Iceland

Wakahama et al. (1977) state that it was Shōda who first studied in detail the growth process and mechanisms of snow accretion on wires. Shōda observed wet snow accreting at temperatures between -1°C and +1.5°C, at wind speeds less than 3 m/s. Wind speeds exceeding 3m/s blew the accreted snow off the wire. The snow accretions observed by Shōda had low densities (0.2 g/cm³). Those findings were published in 1953 in a Japanese article, unavailable in English.

In comparison, Sakamoto (2000) reports that dry snow accretions are easily blown from wires at wind speeds exceeding 2 m/s, and that they rarely exceed a density of 0.1 g/cm³.

Considering the range of temperatures and the low wind speeds, it would appear that Shōda was describing a mix of dry and wet snow accretions similar to the kind of accretions often found in France. Admirat et al. (1990), in their summary of the observations and measurements of the French wet snow program of 1983-1990, reported that a succession of dry and wet snowflakes were often observed at temperatures around 0°C. Accretion densities were observed between 0.10 and 0.22 g/cm³, at wind speeds between 0 and 5 m/s.

A comparison of wet snow data reported by monitoring programs in France, Japan and Iceland is presented in Figs.10 and 11. Other countries such as Canada, USA, UK, Norway and Slovenia also experience wet snow falls that affect their overhead transmission network. Wet snow accretion occurrences are not as common or as catastrophic, in these countries, as they are in France, Japan or Iceland.

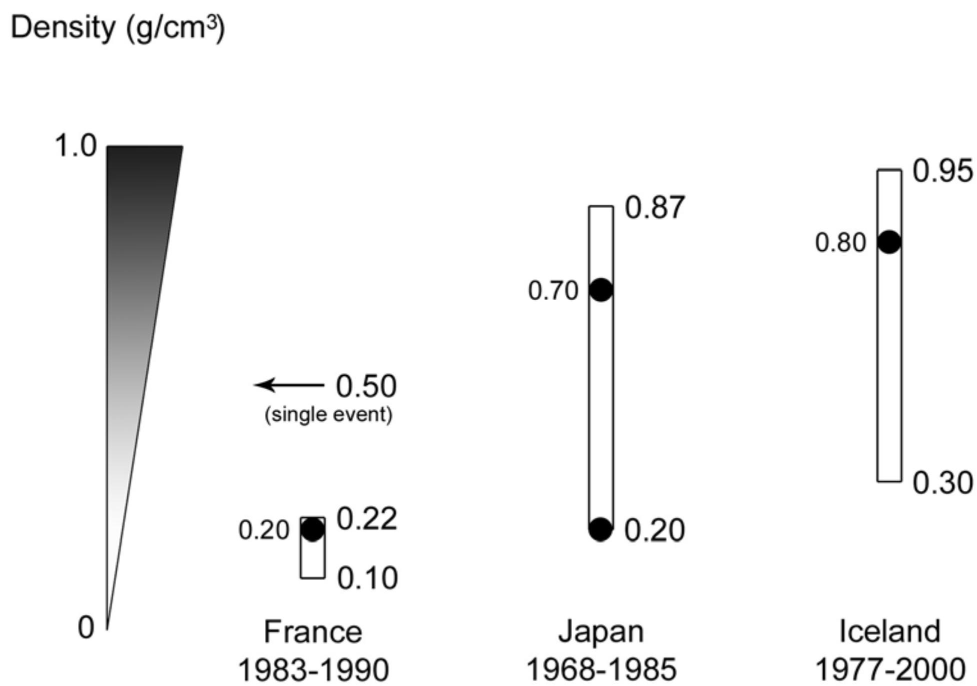

Fig.10 Density of wet snow accretions on overhead wires reported in three studies
(data from Admirat et al. 1990, Wakahama et al. 1977, Sakamoto 2000, Elíasson & Thorsteins 1996)

In Fig.10, the black dots mark peaks in the wet snow density distributions. Two peaks are found in the data from Japan, corresponding to two distinct synoptic weather conditions, as described by Wakahama et al. (1977). “Monsoon-induced snow accretions”, as observed by Shōda (reported by Wakahama et al. 1977) occur at low wind speeds and produce low density accretions (0.2 g/cm³), whereas “cyclone-induced snow accretions” are more severe, occur at high wind speeds and produce high density accretions (typically 0.7 g/cm³).

	France (1983-1990)	**Japan** (1968-1985) "monsoon" type	"cyclone" type	**Iceland** (1977-2000)
Wind Speeds (m/s)	0 - 5	0 - 3	> 10	10 - 25
Density (g/cm³)	0.10 - 0.22 0.50 (single event)	0.2	0.2 - 0.87	0.3 - 0.95
Snow Overload (kg/m)	0 - 10	0 - 5	0 - 15	0 - 20

Fig.11 Density, wind speeds and snow overload comparison for the studies carried out in France, Japan and Iceland (data from Admirat et al. 1990, Wakahama et al. 1977, Sakamoto 2000 and Elíasson & Thorsteins 1996)

The research efforts displayed by Japan and France suggest that they are vulnerable to wet snow accumulation on overhead wires and structures. Their historical records show that they are at risk of being subjected to severe wet snow storms.

Sakamoto (2000) reports only 14 noticeable wet snow incidents in Japan, from 1962 to 1985. Wet snow falls do not occur often in Japan: on average, only once or twice a year, with noticeable storms once every three years or so (Sakamoto 2005). For the last 50 years, the Japanese records do not show cases of recurrence of severe wet snow incidents in a relatively small area; installing an instrumented test line in Japan has little chances of providing useful data on wet snow accretion (Sakamoto et al. 2005).

In France, wet snow falls occur on average two to three times a year; there have been several winters without such events, and some with up to seven wet snow episodes (based on 30 years of data given Strauss (1986)). The data reported for France in Figs.10 and 11 only represents the data collected during a 7-year monitoring program, from 1983 to 1990. It should not be used to draw conclusions as to the typical densities of accreted snow that can be found in France.

Iceland records on average 8 to 10 wet snow episodes each year (Elíasson & Thorsteins 1996). In many cases the events are very localized but in other cases they cover half of the country. Test spans of overhead wires are currently being monitored in Iceland.

4.2 Wind tunnel experiments

Wet snow accretion on an overhead wire has been studied in laboratories by using wind tunnels. Such experiments have been carried out in Japan since the 1970's. Wet snow wind tunnels were originally used to study the growth of wet snow accretions, their adhesive properties, their textures and the trajectories of individual snow flakes as they impact or pass by a wire (Wakahama et al. 1977). Wet snow can be made artificially by using natural dry snow or finely crushed ice: in the wind tunnel, wet snow is obtained either by heating dry snow or by injecting a water spray along with crushed ice (or dry snow). During the 1980's wind tunnels were used to develop and validate wet snow accretion models; these studies, led by Sakamoto and Admirat, examined the dependence of meteorological parameters on snow accretion on overhead wires (Sakamoto et al. 2005).

The experiments were successful in determining the effects of varying key parameters. In order to perform a large number of experiments within the allowable time, parameters such as precipitation intensity and ambient air temperature were increased. These modifications impaired the equivalence between the experimental and natural conditions (Sakamoto et al. 2005). In Japan, wet snow wind tunnels were occasionally used in the 1990's and in 2000 to study accretion shapes and the effect of conductor diameter on the size of wet snow sleeves (Yukino et al. 1998, Shugo et al. 2002).

5. Wet snow shedding

5.1 Observation of wet snow shedding in wind tunnels

Results from wind tunnel testing indicate that wet snow accreting and shedding from an overhead wire is a random process. On a cable section, under the same experimental conditions, snow either accretes as a full sleeve or sheds before it has a chance to form a full sleeve. Shedding occurs either along the entire length or in partial segments (Sakamoto et al. 2005).

The following tendencies have been observed during wind tunnel testing:

a) Low density snow tends to shed more easily than higher density snow.
b) High wind speeds tend to hold the accretions onto the wire, even if the eccentric weight and wire twist are large. Accretions formed under high wind speeds do not drop off easily.
c) The probability of shedding does not depend significantly on the air temperature.
d) Accretions tend to shed more easily from torsionally stiff wire.
e) Once a complete snow sleeve is formed it is very unlikely to shed by wind and gravity loads alone.

It should be noted that observations a) to d) apply to accretions that have not yet formed into a complete cylindrical sleeve (Sakamoto et al. 2005).

To be more precise, observation e) should state that a snow sleeve is unlikely to shed in a relatively short period of time after its accretion: as the sleeve warms up and its LWC increases it becomes more likely to shed. It has been described in section 3.3.2 how the natural shedding of a wet snow sleeve occurs in the funicular regime, once gravitational and aerodynamic loads exceed the reduced internal cohesive forces.

Wet snow sleeves melt when subjected to air temperatures above 0°C, solar radiation or wire heating. The liquid water produced by melting flows down to the bottom of the accretion: water droplets may eventually drop from the bottom-side of the snow sleeve. The bottom of the accretion may become saturated with water and appear transparent, while the LWC of the top of the accretion remains more or less the same. Sakamoto has even witnessed cases where the bottom half of the accretion had shed but the top part remained on the wire. The melting phenomenon described above is also observed if the snow sleeve is subjected to rain (Sakamoto et al. 2005).

5.2 *In situ* observation of wet snow shedding

5.2.1 Natural shedding

Field observations show that shedding of wet snow sleeves on overhead wires first occurs close to the towers, i.e. close to the anchor, where cable rotation is prevented or reduced and where axial growth occurs. The remaining accretion is cylindrical (with the maximum diameter at the mid span) and covers most of the wire span: it either sheds partially and randomly over the span, or suddenly along the entire length of the span (Poots 1996).

During wet snow events, successive cycles of accumulation and shedding (saw-tooth loading cycles) have been observed on overhead wires. It is possible to increase the frequency of these cycles by using Joule heating, since increasing the LWC of wet snow sleeves promotes shedding. With Joule heating, the maximum snow overload can be controlled and limited to a predetermined “safe” level. Joule heating may also be used to delay the beginning of the accretion during a storm (Grenier et al. 1986).

Poots has been developing mathematical models of snow and ice accretion based on basic thermodynamics, heat transfer and fluid flow. These accretion models are far from being empirical and have been summarized in a book (Poots 1996). Even the most complex of these models relies on basic physical mechanisms. A continuation to his work could eventually lead to a 3-dimensional, time-dependent model of the growth, persistence and shedding of snow accretion on an overhead wire that would be valid for a full range of precipitation rates, temperatures and wind speeds. Given the meteorological parameters of a snow storm as inputs, such a model would be very useful to predict the amount of accumulated snow on wires. Saw-tooth loading cycles could also be predicted, as well as the amount of Joule heating necessary to limit overloads (or even to ensure shedding before overnight freezing).

Based on the observations of Pierre Guilbeault, a testing engineer at Hydro Québec's Research Institute (IREQ), it would seem that the shedding "mode" depends on the cable diameter. During a wet snow event that occurred in the province of Québec (Canada) on March 22nd 2001, he made some observations on the wet snow that had accumulated on the Hydro Québec experimental line: the shedding of larger and stiffer wires was random and piecewise. Smaller wires, such as traditional overhead ground wires, shed by "unzipping" along their entire length, which caused large oscillations. Some of the fallen accretions were weighted and the snow overload was roughly estimated at 5kg/m (Guilbeault 2005). Observations were made on the day of the storm, when snowfalls were moderate. Weather conditions reported for this event (30 hours) are as follows: 40 to 60 cm of snow precipitations, sometimes heavy, air temperature between 0°C and 1°C, wind speeds between 10 and 15m/s (see Web reference).

Pierre Guilbeault's observations enable us to propose a hypothesis concerning the unzipping mode of shedding of an overhead wire: there must be a critical ratio of accretion diameter to cable diameter that needs to be exceeded in order to have unzipping. This critical ratio is probably also dependent on the density and LWC of the snow.

There may also be other modes of wet snow shedding. For example, partial unzipping may start from one end of the sleeve and stop after a given length, and then repeat itself in a cyclical fashion until all of the accretion is shed; mixed modes of shedding may also exist. Unfortunately, the available literature lacks descriptions of *in situ* shedding.

5.2.2 Natural shedding after overnight freezing

Natural shedding strongly depends on the weather conditions following the accretion. During the wet snow event described by Guilbeault, the air temperature was more or less steady and always greater or equal to 0°C. However, if a wet snow sleeve is subjected to overnight freezing it is unlikely to shed all at once. It will persist on the wire and shed in the same manner as rime ice and glaze ice: by slow sublimation and/or melting (if the temperature gets above the freezing point). Such accretions can persist for many weeks on a wire (Elíasson & Thorsteins 2000).

The photograph in Fig.12 was taken from a report issued on January 18th, 2005, by the Nova Scotia Utility and Review Board. On November 13th and 14th, 2004, a major storm struck the province of Nova Scotia (Canada): it was characterized by strong winds, temperatures close to the melting point and large precipitations in the form of wet snow, sometimes accompanied by ice pellets and rain.

The picture, taken three days after the storm, shows a high density accretion that is still holding to half of the wire span.. A particular feature in this picture is the wire showing out of the snow sleeve on the left-hand side. This may be giving a hint as to how this sleeve was shedding prior to freezing.

Fig.12 Wet snow sleeve still holding to a wire, November 17th, 2004
(from the report issued on January 18th 2005 by the Nova Scotia Utility and Review Board on the wet snow storm of November 13th and 14th, 2004)

5.2.3 Forced shedding

Poots (1996) suggests that wet snow accretions may also be shed by some or all of the mechanisms observed for glaze ice and rime ice. Intuitively, a sudden twist given to an accreted snow sleeve, or a significant bending moment induced by a propagating wave (e.g. a propagating impulse on the cable) should be sufficient to fracture and shed the accretion. However, there is no field observation to confirm this.

6. Snow mechanics

In the literature, there is no mention of any material testing ever performed on wet snow sleeves, either from field samples or wind tunnel experiments. One of the biggest difficulties to expect when attempting to measure the strength of a snow sleeve comes from the fact that these accretions evolve rapidly: field samples are typically collected hours, or even days following accretion (or shedding). So far, artificial snow with physical properties and microstructure approaching that of natural wet snow has not been generated for material testing, in a research laboratory.

The subject of wet snow mechanics is practically inexistent. However there has been some work done in dry snow mechanics. Intuitively, wet snow in the pendular regime (i.e. at low LWC) and dry snow should exhibit similar behavior under given loading conditions, since they are made of the same constituents and their internal structure is somewhat similar.

6.1 Current state of knowledge of dry snow mechanics

Shapiro et al. (1997) published the most recent review on the state of knowledge of snow mechanics. They reviewed the cumulated research work relating to practical engineering applications. Unfortunately, their review was limited to dry snow: this is not surprising since most of the work done so far in snow mechanics dealt with dry snow at sub-freezing temperatures, with the exception of a few scattered cases where snow properties were measured close to the melting point.

The mechanical behavior of dry snow has been studied to some extent, but not thoroughly. Pertinent data on the mechanical properties and deformational behavior of snow has been gathered since the 1930’s. Mechanical properties of snow were first measured during avalanche studies in Switzerland, and were compiled by Bader in 1939. In the 1950’s and 1960’s numerous experimental observations were made at the U.S.

Army Corps of Engineers' Cold Regions Research and Engineering Laboratory (CRREL). During the same period, Canada, Switzerland and Japan also conducted a considerable number of laboratory and *in situ* experiments.
Up to the late1960's, most of the experimental work was devoted to develop equations of linear elasticity, viscosity and visco-elasticity. In the 1970's, emphasis was put on developing nonlinear deformation and fracture theories. Work was also done to develop constitutive relationships based on the study of the microstructure of snow during deformation.

Most of the studies on snow mechanics were motivated by research in the fields of snow roads and runways, avalanches and vehicle mobility. Compressive, tensile and shear experiments have been performed on dry snow samples, in laboratory environment or *in situ*.

The existing data on the mechanical properties of snow are usually organized and presented as a function of the density of snow. However, snow density alone is not a reliable parameter to describe these properties: for a given temperature and loading conditions, the response to load depends primarily on the microstructure (grain shape, size, number of bond density, etc.).

At present, there is no workable method to relate the observable features of snow (i.e. snow type, grain size and shape, density, liquid water content, temperature) to its response when subjected to a given load. The mechanical properties have been determined experimentally for a few cases and the constitutive relationships developed so far are unable to describe the behavior of snow over its full range of deformation (Shapiro et al. 1997).

6.2 Qualitative deformation properties of dry snow

In this section, it is interesting to outline some of the properties of dry snow when subjected to different loading conditions as these may, up to a certain extent, also apply to wet snow in the pendular regime (low LWC).

Langham (1981) gives a good explanation of the elasto-plastic behavior of snow:

"Snow may be deformed elastically when subjected to a small load applied for a short period of time. Under these conditions the strains are small enough not to disrupt the grain structure and are recoverable once the stress is removed. Snow also deforms continuously and permanently if a sustained load is applied; this is referred to as creep or viscous plastic flow. Strictly speaking, plastic flow requires a threshold stress to be reached before flow can start. However, for snow this stress is so small that it cannot be measured and so snow is referred to as a visco-plastic material."

The deformation of dry snow is characterized as follows (Fukue 1977, St. Lawrence & Tang 1980):

- loading rate dependent
- history dependent
- temperature dependent
- undergoes large deformation before fracture
- stiffening behavior under compressive load (stiffness increases as strain increases)
- softening behavior under tensile loading (stiffness decreases as strain increases)

Some of those aspects can be seen in Fig.13. The loading rate affects the failure type: ductile failure occurs at low deformation rates, brittle failure at high deformation rates. Grain metamorphism from dendritic snowflakes to spherical shapes is also found in dry snow, along with an increase in cohesive strength: the rate of metamorphism is slower in dry snow than in wet snow, taking place over a period of time measured in days, weeks or even months. In this particular case, snow that is six days old exhibits 10 times the compressive strength of fresh snow (30 minutes old).

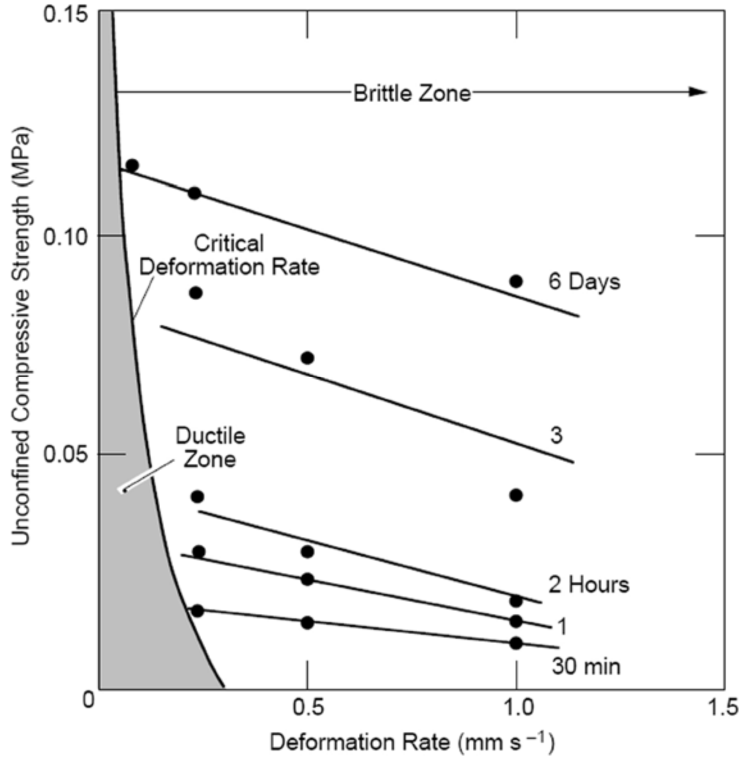

Fig.13 Unconfined compressive strength vs. deformation rate
15-cm-long snow samples of various ages
(from Fukue, reproduced in Shapiro et al. (1997))

The difficulties encountered when attempting to describe the mechanical properties of snow in a general way are well illustrated by Fukue (1977) when he compares the mechanical properties of dry snow to those of sand and clay. The variation in the nature of snow, from fresh powder to something close to ice may in fact be similar to the variations found between sand and sandstone, or clay to shale.

7. Summary and conclusion

Wet snow typically occurs at air temperatures slightly above the freezing point. Its accretion on overhead transmission line conductors and ground wires can lead to a number of serviceability, safety and mechanical reliability issues.

Wet snow particles carried by the wind adhere to an overhead wire and the accreted mass grows out into the wind causing an eccentric load on the windward side of the wire. Wind is responsible for packing the accreting snow grains to a high density. During a storm the densities of the accretions on overhead wires are normally much higher than the densities of snow accumulating on the ground. Two modes of accretion have been observed along the span of a wire: axial growth and cylindrical sleeve growth.

The physical properties of wet snow are extremely variable. Different ratios of ice, water and air produce microstructures with different densities and liquid water contents. This, in turn, leads to a wide range of adhesive properties and strength.

Moreover, the microstructure of wet snow is continuously evolving and it undergoes metamorphism with changes in liquid water, temperature and/or temperature gradient. Accretions often shed naturally within a few hours, but may persist on the wire if subjected to sub-freezing conditions. The mechanical properties of freshly accumulated wet snow may be very different from those of shedding wet snow.

Wet-snow accretions are difficult to study. They are rare and often limited to specific locations with special topographic or microclimatic conditions. Field observations are typically made several hours or even days following a storm. Laboratory experiments simulating wet-snow accretions have been performed in the past using wind tunnels. However, experimental and natural conditions were not equivalent.

In the literature, there is no mention of actual material testing on wet-snow sleeves, either from field samples or wind tunnel experiments.

Snow is considered to be a visco-plastic material. The mechanical properties of dry snow depend on its deformation path. Its failure type depends on the deformation rate: at low strain rates snow is ductile, at high strain rates it is brittle. Dry snow exhibits a stiffening behavior under compressive loads, and a softening behavior under tensile loads. In the pendular regime, wet snow may exhibit deformation behaviors similar to dry snow.

This review serves as a first step towards modeling the dynamic response of overhead wires and towers induced by wet snow shedding from a wire. It has been shown in this review that many aspects of the physics of wet snow require further investigation. One lacking aspect which is crucial to the success of the dynamic response model is the mechanical properties of wet snow. These properties could be estimated crudely from the existing dry snow literature, but these would not take into consideration the effect of the liquid water contained in the snow matrix.

Determining the mechanical properties of wet snow for a full range of density and LWC values is beyond the scope of a master's project. As the next step in this project, it has been proposed that wet snow experiments be carried out using the facilities of CIGELE at the Université du Québec à Chicoutimi. Such experiments could provide a more accurate estimate of the mechanical properties of wet snow on a wire, for densities and LWC values limited to the required range of interest.

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