SNOW CREEP AND GLIDE FIELD MEASUREMENTS: IMPROVEMENTS FOR DESIGN OF GAS-BASED REMOTE AVALANCHE CONTROL SYSTEMS

Adam Davis[1], Anton Avchyan[2]

[1] *Park City Mountain Resort, Park City, UT, USA*
[2] *Wasatch Geotech, Murray, UT, USA*

ABSTRACT: Snow creep and glide forces in alpine environments contribute to structural damage and midwinter failure of remote avalanche control systems (RACS), particularly affecting near-land-surface components such as gas lines. Models that describe sustained gravitational forces in slowly deforming snowpack exhibit notable regional bias and rely on limited field validation in North America. Although some validation exists for large structures such as snow-supporting structures and lift towers, significantly less attention has been paid to forces acting at the snow-ground interface, where land-cover properties strongly influence creep and glide behavior. This gap is critical for gas-based RACS, where gas lines extend through starting zones, exposing large segments of near-surface infrastructure to snow pressure.

This work reviews the current literature on snow creep and glide in engineering design, including foundational European and American guidelines, and recent advances in field instrumentation and monitoring. The review identifies key limitations in existing models, particularly the uncertainty associated with ground-surface coefficients, the need for standardized treatment of surface conditions, and the lack of direct force measurements at the snow-ground interface. These limitations suggest that current design practices may not adequately represent real-world loading conditions for near-surface infrastructure. To address this gap, the study proposes a field-based conceptual framework to directly measure basal creep and glide forces and evaluate the influence of ground surface characteristics.

KEYWORDS: Planning and Engineering; RACS Installation and Maintenance; Snow Creep; Glide

1. INTRODUCTION

Gas-based remote avalanche control systems (RACS) deliver gas through anchored or buried supply lines extending into avalanche starting zones. Installing and protecting these lines is costly and snow loading can damage them. Loading develops when downslope snow creep and glide are interrupted (Salm, 1977). Its magnitude depends on factors including snow depth and density, temperature, slope inclination, and ground-surface roughness (McClung, 1975). Although established design methods address snow-supporting structures and vertical masts and suggest low creep forces near the ground, the guidance does not provide a procedure specific to low-profile gas lines. This paper assesses existing snow-pressure models in relation to near-ground infrastructure and introduces a field experiment designed to quantify both the magnitude and temporal evolution of reaction forces on a low-profile element at the snow-ground interface. The resulting dataset will facilitate comparison with current design and inform future RACS installations.

* Corresponding author address:
Davis Adam, Park City Mountain Resort,
Park City, UT 84060;
tel: +1 410-746-4535;
email: adamdavis171@gmail.com

2. EXISTING DESIGN APPROACHES TO CREEP AND GLIDE ESTIMATION

Creep and glide are related processes within the snowpack that affect mountain infrastructure. Both phenomena generate significant forces when obstructed by downslope obstacles, potentially damaging ground surface objects that lack adequate anchoring or protection, natural or engineered (Larsen and Laugesen 1990; Margreth, 2007b; Holler, 2009). To address this hazard, various physical definitions and mechanical formulations of both processes have been tested against field experimental data (Salm, 1977; McClung et al., 1975, Larsen et al., 1985). Although these models have been applied to supporting structures and masts, load measurements remain limited for small linear components at the ground interface.

2.1 Creep and glide mechanisms

On inclined slopes, the weight of the snow cover and gravitational force produce stress components both parallel and perpendicular to the slope surface, resulting in three deformation and movement processes: vertical settlement, downslope internal shear deformation and basal glide along the snow-ground interface (Figure 1) (Salm, 1977; McClung & Larsen, 1989; Margreth,

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2007). Their conceptual relationship may be expressed as:

$$v_{creep} = v_{set} + v_{sh}$$
$$v_{total} = v_{creep} + v_g \quad (1)$$

where v_{set} is the slope-normal settlement velocity, v_{sh} is the downslope internal shear-deformation velocity and v_g is the basal glide velocity. The first two components together constitute snow creep force, whereas glide represents basal slip of the snow cover over the land surface, such that the entire snowpack is involved in downslope movement (McClung, 1975; Salm, 1977; Jones, 2004; Ancey and Bain, 2015). When the combined movement is restrained by an anchored object, stresses are redistributed through the snowpack and produce the resultant structural load shown in Figure 1.

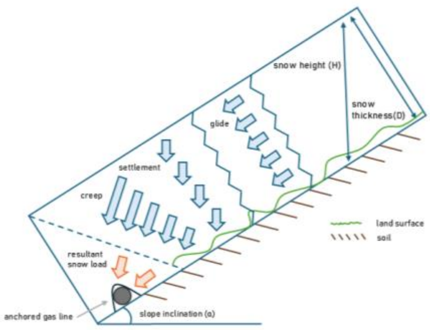

Figure 1: Schematic representation of the snow forces acting on a ground surface linear infrastructure element.

Snow creep is a distributed, time-dependent deformation that acts throughout the layered snowpack. The snowpack compacts while simultaneously deforming and stretching downslope (McClung, 1975; Salm, 1977; McClung & Larsen, 1989; Shapiro et al., 1997). Laboratory and field studies show that snow cannot be represented by a single stationary viscous relationship because its deformation depends nonlinearly on time, stress, density, temperature, bonding, microstructure and liquid water content (LWC) (Shinojima, 1967; Salm, 1982; Theile et al., 2011). Low-density snow may initially undergo rapid settlement and downslope shear, while densification, sintering and seasonal metamorphism progressively modify its stiffness and deformation rate. Although creep generally decreases as snow densifies, warming and wetting can rapidly increase deformation by weakening bonds and accelerating grain rearrangement (Conway et al., 1996).

Creep and the resulting structural loading therefore vary throughout both the winter season and individual weather events. Seasonal accumulation increases snow depth, density and LWC, while snow metamorphism alters how those loads are transmitted through the snowpack layers. Measurements have identified short-term pressure fluctuations during spring warming and subsequent cooling or refreezing (Hewes, 2023; Börner et al., 2024). Microstructural simulations further supported that creep and strain hardening emerge from the evolving snow structure and deformation of the ice matrix (Theile et al., 2011). These relationships vary between snow climates: measurements from maritime western Norway, the European Alps and the limited North American field record exhibit different seasonal loading behavior (Larsen, 1998; Höller et al., 2009; Hewes, 2023). Consequently, relationships calibrated for one region may describe the first-order influence of snow depth and density but may not reproduce the magnitude or timing of creep-related loading under different climatic conditions.

Basal glide is controlled by the mechanical and hydrological condition of the snow-ground interface (Jones, 2004). Early engineering descriptions related glide to slope inclination, aspect, ground roughness and an interface temperature near the melting point (Salm, 1982). McClung (1975) represented the resistance produced as basal snow deforms around ground irregularities using the stagnation depth. Subsequent field studies demonstrated that topography alone does not describe this boundary (Holler, 2009). Long grasses and flexible shrubs may be compressed into a relatively low-resistance surface, whereas woody vegetation and connected surface obstacles can anchor the snowpack more effectively (Fromm et al., 2018; Holler, 2009; Newesely et al., 2000).

Liquid water supplied by rainfall, surface melt, or ground heat can soften basal snow, reduce contact with roughness elements and increase glide displacement (Jones, 2004). However, the importance of water, soil moisture, soil temperature and slope geometry varies between sites and throughout the season (Maggioni et al., 2019; Fromm et al., 2018). Ancey and Bain (2015) consequently described the interface as spatially heterogeneous, involving discontinuous water-filled cavities and temporary losses of basal resistance. Two surfaces assigned the same qualitative “smooth” or “rough” classification may exhibit different resistance. Likewise, temporal rates of snow gliding can differ substantially between areas and seasons. This variability limits the transferability of empirical glide factors and supports the need to measure basal displacement and interface conditions along with the snow force exerted on near-ground infrastructure.

Structural snow pressure, independent of avalanche impact load, develops when an obstacle restrains creep and glide. As downslope movement interacts with an obstacle, a back-pressure zone develops in which the snowpack stress field is redistributed, and normal and shear forces are transferred to the structure. The formulation by Salm (1977) represented a rigid, full-depth supporting surface extending indefinitely across the slope, allowing plane-strain deformation without lateral end effects. This idealization subsequently became part of Swiss and related European design practice (Margreth, 2007a; Austrian Standards International, 2024).

McClung (1976) distinguished pressure associated with restrained transverse deformation from the additional pressure generated by interruption of creep and glide. He demonstrated that the magnitude, distribution and upslope influence length of loading depends on both snow load and boundary condition at the snow-structure interface. He further reduced this representation to a simplified model for the average pressure and back-pressure-zone length near the center of a long barrier (McClung, 1982). Subsequent field comparisons showed that snowpack variability and boundary conditions could produce loading not fully represented by a uniform linear material (McClung and Larsen, 1989).

Finite-width structures create a different loading configuration because snow can deform around their lateral edges, producing three-dimensional end effects (Salm, 1977). Subsequent Norwegian measurements on isolated tubular masts demonstrated that load and effective influence width depend on mast diameter and seasonal snow temperature, although these experiments were conducted under negligible-glide conditions (Larsen et al., 1989; Larsen and Laugesen, 1990; Larsen, 1998). Margreth (2007b) considered Alpine masts exposed to stronger glide and demonstrated the importance and uncertainty of empirical efficiency and glide factors.

A gas supply line does not directly correspond to either configuration as snow may pass over or bridge across it rather than being restrained through its full depth. Its loading depends on pipe orientation, anchored or embedded, anchor spacing, surface conditions and three-dimensional stress redistribution around the pipe and its anchors. Existing wall and mast studies therefore do not represent gas-line loading, providing the principal justification for more specific field measurements.

2.2 Existing engineering models and guidance

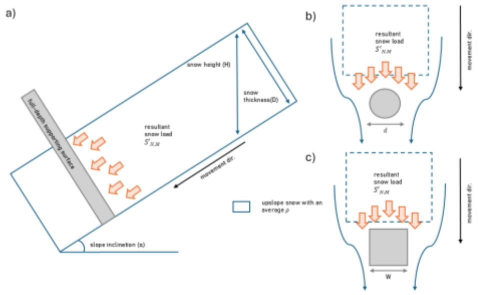

Figure 2: a) Downslope load $S'_{N,M}$ on a structure. b) Snow deformation around finite-width obstacle according to Larsen, 1998. c) Snow deformation around finite-width obstacle according to Margreth, 2007a.

The Swiss design guidance estimates the resultant load generated upslope of a rigid supporting surface (Salm, 1977; Margreth, 2007a). Its reference interpretation is a full-depth surface normal to and extending indefinitely along the slope. The slope-parallel line load is:

$$S'_N = \frac{\rho g H^2}{2} K N \; [kN\, m^{-1}] \qquad (2)$$

where ρ is average snow density, H is snow height, K is empirical creep factor related to density and slope inclination, and N is a glide factor assigned from expected glide intensity, aspect and ground-surface class. The approach is practical because these inputs can be estimated during design, but the empirical treatment of glide and creep introduces substantial uncertainty.

For a finite-width structure, the Swiss method applies an efficiency factor (Eq. 3) to account for three-dimensional flow around its lateral ends.

$$\eta_F = 1 + c\frac{D}{W} \qquad 0.6 \le c \le 6 \qquad (3)$$

and the slope-parallel force becomes (Figure 2a):

$$S'_{N,M} = S'_N \cdot \eta_F \cdot \frac{W}{D} \; [kN\, m^{-1}] \qquad (4)$$

where W is the structure width, D is snow thickness normal to the slope and c represents snow-depth and glide conditions. The increasing efficiency factor for smaller objects reflects the influence of end effects on narrow structures (Figure 2c). However, both formulations assume a supporting surface extending vertically through the snow cover. They do not describe the limited obstacle height, snow bridging or load transfer associated with a low-profile line at the basal interface (Margreth, 2007a; Rudolf-Miklau et al., 2015). For thin ropes and bars, the guideline requires a substantially increased η_F, but acknowledges that its value is based only on rough estimates. In the Technical Avalanche Handbook (Rudolf-Miklau et al., 2015) an example with 200 cm snow thickness and a cable diameter of 1 cm suggests η_F of ~50.

McClung continuum-mechanics model later was used for comparison with the Swiss and Norwegian design models and their validation (McClung et al., 1984). His model predicts average pressure and back-pressure-zone length near the center of a long barrier using snow thickness, density, slope inclination, compressibility, creep length and stagnation depth. A later finite-height extension included stresses imposed by snow above a buried wall, but it remained a plane-strain formulation and did not represent flow around a near-ground small element (McClung et al., 1984). Its applicability to the operational task has also remained limited.

Larsen and co-authors (1998) developed an empirical relationship for isolated tubular masts:

$$S'_{N,M} = K_L C \rho g h^2 \sin \sin \alpha \; [kN\, m^{-1}] \quad (5)$$

with the diameter factor

$$C = 0.98 d^{0.63} + 0.42 \quad (6)$$

where $S'_{N,M}$ is the resultant load per unit length acting on the mast, h is snow depth measured perpendicular to the ground, ρ is average snow density, d is mast diameter, α is slope inclination, and $K_L$is an empirical snow-depth factor (Figure 2b). The formulation demonstrated that the influence width of an isolated obstacle can be considerably greater than its physical diameter (Larsen et al., 1989; Larsen and Laugesen, 1990; Larsen, 1998).

These formulations remain dependent on structural geometry, empirical coefficients and locally observed snow conditions. More advanced numerical models can represent transient deformation, temperature-dependent viscosity and evolving snow properties, but require constitutive parameters and boundary conditions that must be independently measured or calibrated (Bartelt and Christen, 2007). Existing analytical and numerical methods therefore provide comparison estimates for the proposed experiment rather than validated design basis for a low-profile gas line.

2.3 Validation and monitoring

Field validation of snow-pressure models has focused primarily on full-depth supporting structures and vertical masts. Beginning in 1985, McClung and Larsen instrumented a Norwegian avalanche-supporting structure with pressure cells and strain gauges and monitored snow depth, density, temperature, stiffness and glide displacement over several winters. The two sensor types produced comparable average pressures under dry midwinter conditions, whereas pressure-cell measurements became more variable during spring warming and wetting. Strain gauges provided more stable estimates of integrated load and its vertical distribution but required temperature correction and structural back-analysis (McClung et al., 1984; Larsen et al., 1985). Later measurements on isolated tubular masts demonstrated the importance of obstacle diameter, snow temperature and three-dimensional stress redistribution, although basal glide was negligible at those sites (Larsen, 1989). Field comparisons further showed that uniform linear material assumptions did not reproduce all observed pressure magnitudes and distributions (McClung and Larsen, 1989).

Additional validation has included back-analysis of failed cableway masts and more recent instrumented supporting structures (Larsen and Laugesen, 1990; Margreth, 2007b). Margreth (2007b) found that loads inferred from three failed Alpine masts were broadly consistent with Swiss design guidance, although failure analysis provides only a lower-bound estimate and no record of load development. In the United States, experiments involving the displacement of various lightweight objects (Caselli, 2004) (e.g. sawdust, ping-pong balls) within the snowpack were followed by similar snow supporting structures studies (Conway et al. 1996). Measurements from Jackson, Wyoming, also showed general agreement with existing analytical models but identified springtime maxima and nonuniform pressure distributions that were not fully represented by simplified assumptions (Hewes, 2023). Börner et al. (2024) demonstrated a lower-cost and scalable monitoring approach while identifying persistent measurement challenges, including temperature sensitivity, baseline drift, friction, settlement loading and structural bending. More recent monitoring efforts have expanded these measurements to include glide displacement, snow and soil temperatures, LWC, soil moisture and structural forces, particularly in the European Alps and Scandinavia where such studies were crucial for glide avalanche studies (De Biagi et al., 2013; Höller, 2014; Humstad et al., 2016; Fromm et al., 2018; Maggioni et al., 2019).

Collectively, these campaigns show that field validation has focused mainly on structures extending through full depth of the snowpack. This motivated the use of a low-profile load-cell assembly rather than a conventional glide shoe.

The proposed experiment offers intermediate configuration by pairing the reaction force measured on a low-profile near-ground element, snow and ground temperatures, soil moisture, meteorological observations and snowpack measurements. Because the load cell records the combined effects of creep and glide, these accompanying observations are required to help interpret individual processes responsible for each loading event.

3. LIMITATIONS FOR NORTH AMERICAN RACS

Publicly available documentation contains little evidence linking snow creep or glide to damaged RACS gas-supply pipelines. Operational practice, nevertheless, indicates that these components are treated as vulnerable: gas lines are anchored, buried, or otherwise protected. For example, an installation at Alta used an anchored steel channel where the pipeline crossed a creep-prone slope (Bressler, 2025). While detachment and warping of the lines were observed, addressing this issue was not prioritized in the design process. As a result, the magnitude, timing, and mechanism of snow loading on RACS pipelines remain unsubstantiated.

Existing design guidance estimates loads on full-depth supporting surfaces or vertical masts. While finite-width corrections account for lateral end effects, they do not define snow depth or influence width contributing to a low-profile element over which snow can deform or bridge. Field measurements address different parts of this problem. Glide shoes measure basal displacement but not the loading on an anchored object. Pressure cells and strain gauges measure reactions on barriers that interrupt the full snow depth and alter the surrounding deformation field.

Although creep stress is expected to decrease near the snow-ground interface, damage to compact linear infrastructure has occurred at sites without documented glide, suggesting that creep alone may generate substantial loads. The principal research gap is not the absence of snow-pressure measurements generally, but the absence of measurements representative of the geometry and basal position of RACS supply lines. The proposed assembly addresses this limitation by measuring the slope-parallel reaction force imposed on a low-profile element of known geometry at the snow-ground interface. Paired snowpack, land surface and meteorological observations will provide the context needed to interpret the force record.

4. RESEARCH QUESTIONS AND HYPOTHESES

The primary objective of this study is to assess whether snow loading on low-profile infrastructure can be measured more directly and representatively than by applying relationships developed for full-depth supporting structures or vertical masts.

The study addresses the following research questions:

1. To what extent can a near-ground load-cell assembly produce a stable and repeatable seasonal record of force on a low-profile linear element?

2. What is the relationship between the magnitude and temporal evolution of the measured force and variables such as snow depth, density, stratigraphy, topography, vegetation, snow and soil temperature and moisture, LWC, and meteorological conditions?

3. To what extent do land-surface properties, such as roughness, vegetation, moisture, and thermal condition, explain differences in force and displacement compared to the empirical surface classes used in existing guidance?

4. Do existing supporting-structure and mast-design relationships replicate the magnitude and seasonal timing of loads measured on a low-profile element, or do they display systematic differences attributable to obstacle geometry and its position at the basal interface?

The following hypothesis will be evaluated: We assume that measurable reaction force will develop during periods with minimal or no detectable basal displacement, as internal snow creep may load the restrained element independently of measurable glide.

The proposed Phase 1 of the study is intended to evaluate the feasibility of measurement and establish an initial force-and-displacement record. Evaluation of surface classes and development of design coefficients will require replicated measurements across multiple surfaces, seasons, and operational installations.

5. METHODOLOGY

This study will deploy load-cell instrumentation at the snow-ground interface to monitor force evolution throughout the winter. These measurements will be paired with snow pit observations and meteorological data to contextualize loading events and identify key factors. The resulting dataset will help evaluate current design coefficients and explore potential refinements related to near-ground snow pressure and the characteristics of small infrastructure elements. Future work will apply this approach to gas supply lines in operational RACS installations, compare measured forces under varying surface conditions, and test proposed design modifications. The experimental setup will be located at Park City Mountain Resort in Utah and will include two test sites (Figure 3). The first site is adjacent to the Bonanza Ski Lift, east-facing, 2812 m a.s.l., with an average slope of 34°. The second site is north of Tri-County Peak, adjacent to the Jupiter Ski Lift, north-facing, 3053 m a.s.l., with an average slope of 32°. Both sites are characterized by Montane Sagebrush Steppe vegetation.

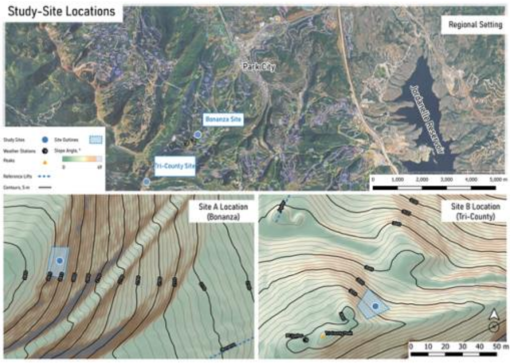

Figure 3: Study site location map in the regional setting with two separate detailed slope inclination shading maps for Site A (Bonanza) and Site B (Tri-County).

The installation of the testing assembly will be performed prior to the winter season 2026/27 or 2027/28 depending on the pending funding for the assembly.

5.1 *Instrumentation and test equipment assembly*

Test equipment per site (Figure 4) will consist of two 1 m^2 by 6.35 mm thick steel plates prefabricated to house the load cells. The self-contained instrumentation will allow for quick preseason installation and seamless removal. Adjacent to the equipment will be a soil moisture and temperature sensor at the snow-ground interface (Maggioni et al., 2019). During the winter monitoring period, measurements recorded by the datalogger will be retrieved approximately once per week. The resulting dataset should contain the force and displacement time series and allow us to identify loading events.

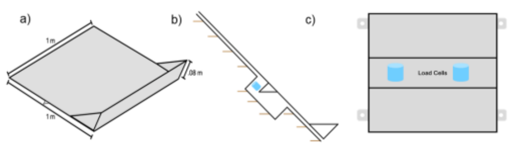

Figure 4: a) Top plate of the test assembly. b) Schematic drawing of a load cell test assembly. c) Base plate with the load cell cavity.

5.2 *Supporting manual observations*

Snowpack conditions at the test site will be assessed through periodic snow pit observations on the instrumented slope. Measurements will include full-depth snow grain types, density, hand hardness, temperature, and total depth, with a focus on LWC and the snow-ground interface. This data will be used to track temporal changes in snowpack structure and evaluate the relationship to measured loads. Each snow pit will be described using the international classification for seasonal snow on the ground (Fierz et al., 2009) and snow, weather, and avalanche guidelines (American Avalanche Association, 2022).

5.3 *Weather observations*

Meteorological data will be collected from NRCS SNOTEL Thaynes Canyon and Park City Mountain Resort PC-Jupiter and PC-Summit weather stations located within approximately 0.5 km of the test sites. Weather observations will provide context for changes observed in snowpack properties and measured loads. Seasonal weather trends will be analyzed to correlate weather, site parameters, and snow deformation. Any anomalies will be documented.

5.4 *Surface and snow spatial variability*

We will document and analyze the boundary conditions between snow and ground by collecting high-resolution UAV imagery at both study sites using a DJI Matrice 4E drone. Snow-free images will be used to create orthophotos for detailed vegetation mapping and to generate a digital surface model (DSM) for microtopography assessment. We will document snow cover accumulation at both sites using a structure-from-motion (SfM) photogrammetry algorithm at fixed intervals throughout the winter season. Data collected with snow present will be compared to the snow-free DSM to quantify snow accumulation. Ground Control Points (GCPs) will ensure precise on-ground coordinates and accurate georeferencing for each flight.

5.5 *Analysis and outputs*

Snow loading records from each test site will be quality-controlled for baseline deviations, temperature response, data gaps, and anomalous measurements. These records will then be synchronized with soil moisture, ground and snow temperatures, meteorological observations, snow-pit measurements, and UAVderived snow depth and land surface data. Loading events exceeding the estimated measurement uncertainty will be identified and characterized by onset, duration, peak force, and rate of force development. Exploratory correlation and multivariable analyses will evaluate relationships between measured loading and variables such as snow depth, density, stratigraphy, temperature, LWC, soil moisture, and meteorological forcing. Following conversion to consistent units and test-element geometry, measured loads will be compared with estimates from existing supporting-structure and mast assumptions to identify differences in magnitude and seasonal timing. Comparisons between the two sites will provide an initial assessment of how aspect, elevation, microtopography, vegetation, and other environmental variables may influence loading and surface coefficients during a single winter.

6. SUMMARY AND CONCLUSIONS

Existing design procedures focus on full-depth supporting surfaces or vertical masts and do not directly address three-dimensional load transfer associated with small linear elements at the snow-ground interface. While empirical glide, creep, surface, and efficiency factors offer useful first-order estimates, they offer limited relevance to RACS gas lines. Evidence suggests that a restrained near-ground element may experience measurable reaction force even when basal displacement is minimal or undetectable, as internal creep can generate loading independently of glide. The proposed experiment will test this hypothesis.

Phase I will integrate reaction-force and displacement measurements with observations of snowpack properties, ground-surface conditions, soil moisture, temperature, weather, and spatial snow accumulation. Synchronizing these data will help identify and evaluate individual loading events in relation to changing environmental and snowpack conditions. Comparison with existing supporting-surface and mast formulations will provide an initial assessment of whether current procedures accurately represent the magnitude and seasonal timing of loads on low-profile elements or reveal systematic differences due to geometry and basal position.

Phase I will establish proof of concept and guide future field experiments. The results will include a repeatable basal-force monitoring procedure, a synchronized, quality-controlled seasonal dataset, a catalog of identified loading events, recommendations for a suitable instrumentation configuration, identification of variables requiring long-term monitoring, and a preliminary evaluation of existing design methods for low-profile infrastructure and operational RACS installations. Ultimately, this work aims to provide an experimentally supported basis for standardizing the design, routing, anchoring, and protection of gas-supply lines and other near-ground infrastructure exposed to snow creep and glide.

This is an early-stage field experiment concept that aims to inform future RACS design and installations. Because published documentation of damage to these components remains limited, observations from RACS designers, installers and operators are particularly valuable. Any feedback is needed and appreciated.

7. LIMITATIONS

The proposed study faces limitations at three stages. During deployment, sensor disturbance from natural snow movement, temperature-induced load-cell drift, snow bridging, anchorage effects, and equipment survivability may affect measurement accuracy. Site access, skier traffic, avalanche-control activities, and avalanches impacting the test assembly may disrupt local conditions. At the interpretation stage, data from only two sites over one winter may not adequately represent the full variability in snow accumulation, ground surfaces, and snow climates. The limited number of surface classes further limits the potential for statistical generalization. The assembly records only the resultant reaction load on the test element. Therefore, creep and glide effects cannot be distinguished independently from the force record and must be inferred from supplementary observations. Finally, extrapolating results from isolated test elements to continuous operational gas lines is uncertain because pipe length, routing, embedment, anchor spacing, and stiffness can influence load transfer. Actual RACS installations face constraints from terrain, construction access, existing infrastructure, and operational requirements, which may prevent consistent installation of idealized design recommendations in the field.

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