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Design and Performance Evaluation of a Semiflexible Snow Barrier for Avalanche Protection

WYDOT Project Champion: Jamie Yount, Avalanche Technician

Joshua Hewes, Ph.D., PE
InterAlpine Associates, LLC
83 El Camino Tesoros
Sedona, AZ 86336

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PROBLEM STATEMENT

This project will provide valuable information on the design and performance of a lightweight, easily constructible snow supporting structure for avalanche starting zones, to be used for the purpose of avalanche risk reduction near transportation facilities within the State of Wyoming. For many decades, the Wyoming Department of Transportation (WYDOT) has managed the danger to motorists traveling on roadways adjacent to known avalanche paths using active defense measures. These measures typically require winter maintenance staff to forecast potential for avalanche activity and when the probability of slides becomes significant, enact road closures and use artillery or explosives to artificially release avalanches. If crews are successful in triggering a slide, snow-moving equipment is brought in to clear the debris before the road is reopened. This approach requires *immense personnel resources* and carries the inherent *risk* involved with detonation of artillery/explosives. The alternative to active control is passive, avalanche starting zone constructed defense that operates stand-alone with no need for WYDOT staff during winter, and that virtually eliminates danger to the traveling public in mountainous areas.

The prototype system being proposed for evaluation is based on a new type of "snow umbrella" used successfully in Europe to retain snowpacks vulnerable to natural release, and consists of wire netting grid supported by only two structural steel cross members and with one foundation per unit. This type of system has the following potential benefits:

1. *Lightweight* – less than approximately 450 lbs per unit for the tallest expected unit.
2. *Adaptable* to any terrain condition because of three-point bearing/connection to ground.
3. Self-reacting structural system requires only one ground anchor foundation per unit, which can be installed with hand tools, and therefore *minimizes construction time* and *disturbance* to the site.
4. Units can be placed in groups side-by-side and sited in irregular patterns to *minimize visual impacts* to the surrounding landscape.
5. *Minimal visual impact* to landscape because of the limited number of large components.
6. Relatively *easy installation*: can be flown into remote sites in groups, and anchored to one ground anchor per unit by hand (no large powered construction equipment necessary for construction at the site).
7. Expected to be very *cost-effective* based on above characteristics.

There are no design standards, either European or domestic, specifically focused on this new type of "snow supporting umbrella" (SSU), although the Swiss Guide [1] could be used to generate snow loading forces. This project aims to first develop design criteria and a generic design process for implementation of this type of system for any general avalanche site. An optimized geometry of structural members and grid netting percent open area would be determined. A site-specific design would then be developed for a location of WYDOT's choosing (with recommendations included herein), and construction and installation of series of SSU at the site would follow. Finally, instrumentation would be used to experimentally measure the performance of the SSU *in-situ* and based on the collected data, final recommendations for future implementation of SSU would be developed.

Two additional aspects are of particular importance with this project. First, there have been concerns about the lack of redundancy of the single point connection to earth and the potentially adverse consequences of a ground anchor failure. One novel approach proposed herein is the use of a “fuse” at the connection to the ground anchor that limits loads imparted to the foundation: if snow forces become larger than that used in design, a yielding link with a precise load capacity will begin to deform plastically so that no additional load can be transmitted to the foundation. Secondly, this project proposes to design and install several SSU at the Milepost 151 Avalanche site near Jackson, Wyoming where a different type of snow supporting structure (SSS) has been used successfully to prevent natural release of avalanches big enough to reach US 89/191. Since installation of the current SSS deployment at the Milepost 151 site, small naturally released slides have occurred and although these have not reached the roadway, they have struck several of the SSS at the site. Installation of these new SSU at the Milepost 151 site would thus serve an operational purpose of protecting the existing SSS which were not designed to “catch” an avalanche – i.e., they were not designed for the very large dynamic forces that are associated with a moving mass of snow.

BACKGROUND STATEMENT

There is a long history of use of constructed avalanche defense systems across Europe, whereas in the United States the last 50 years of avalanche mitigation has focused on mitigating danger by artificial release of snow avalanches via detonation of hand charges in the starting zone or by impact in the starting zone by projectiles fired by artillery. More recently, the Wyoming Department of Transportation (WYDOT) has embraced the concept of limiting the ability of avalanches to release by retaining the starting zone snowpack in place with snow supporting structures (SSS). This approach is termed “constructed avalanche defense”. Strictly speaking, SSS are any type of structural system installed across a potential avalanche starting zone that has a purpose of holding the snow in place so that release is precluded, and SSS are classified as either rigid, flexible, or semiflexible. In the last five years, WYDOT has deployed a series of rigid “snow bridges” at the Milepost 151 Avalanche near Jackson, Wyoming and this system has eliminated the natural large snow slab avalanches that historically reached U.S. Hwy 89/191 at a frequency of once or twice per winter season. The impact of this strategic move away from active control with explosives has been to eliminate the need for WYDOT maintenance personnel during intense storm periods since they must no longer monitor conditions at the avalanche site to decide if road closures are prudent. Figure 1 displays a snow bridge (or SSS) installed at the Milepost 151 site.

Distinctly different, yet with the same aim of retaining large swaths of snowpack in the starting zone, are flexible and semiflexible snow supporting structures which utilize an interwoven fabric of steel netting as the snow supporting surface. Snow nets are flexible systems that utilize the netting spanning between upright poles, which must be anchored with numerous cables to provide system stability (see Figure 2). This system has a primary disadvantage of requiring a relatively complex system of guy cables connected to ground anchors, which results in more intensive construction effort. A relatively new development in Europe has been the semiflexible system that uses a combination of crossbeams and wire rope netting but requires only one anchor point to ground upslope of the unit. These SSS have been termed “snow umbrellas”, and are referred to as snow supporting umbrellas (SSU) herein. Figure 3 provides a photograph of a series of SSU installed in the French Alps region.

Fig 1. Milepost 151 snow supporting structure with monitoring instrumentation.

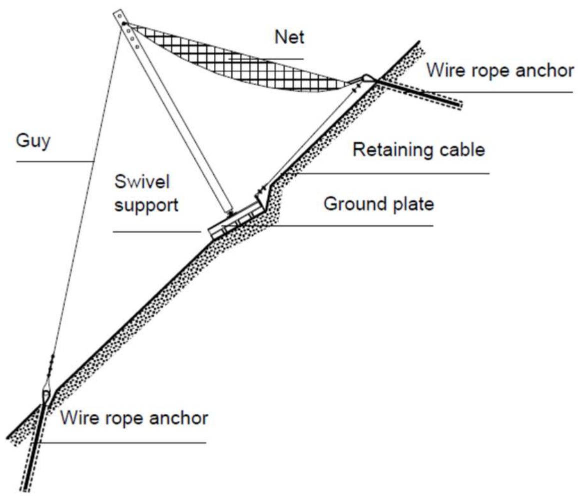

Fig. 2. Sideview of snow net retaining system

Fig. 3. Semi-rigid snow supporting structure at Val Thorens Ski Resort, France.

While SSU have been used in Europe they have not been evaluated for avalanche mitigation in the United States. Researchers in Europe have just recently begun formal research investigations for this new type of snow supporting structure but have yet to develop and/or publish specific design standards based on their findings [2]. There are many unknown aspects in application of SSU including:

- Basic structural design process.
- Optimum geometry and layout of structural members.
- Best practices for connection details between members, netting, and foundation.
- How SSU respond to "end effect" loading, which occurs at the ends of long rows of SSU, and how to best harden the SSU against these additional significant force effects.

SSU also have the potential advantage over rigid SSS because of the reduced number of ground anchors needed – one for a SSU unit versus four to six for a single rigid SSS. A reduction in the required number of foundations will result in less total disturbance to the environment during construction, increased efficiency in speed of construction, and decreased overall project cost. Moreover, one possibility with SSU is that ground anchor foundations can be installed with small hand operated power tools instead of the large tracked drill rigs that are needed to install rigid SSS ground anchors. Finally, because a SSU unit weighs significantly less than one rigid SSS, several units can be flown into position with one helicopter trip rather than a single trip per rigid SSS. Helicopter "tach time" is a significant expense during construction of starting zone defense systems, since these deployments are typically in hard to reach and steep slopes.

Finally, although danger to motorists traveling along US 89/191 below the Milepost 151 avalanche has been essentially eliminated, risk of damage to the installed SSS there remains, based on observations during the 2014-2015 winter season. Figure 4 illustrates a small slide that occurred during late January 2015 that was stopped by impact on SSS positioned below it (light red highlighted region shows approximate extents of the released snow slab). This area sits in the uppermost reaches of the Milepost 151 starting zone. Figure 5 shows a view downhill from the upper slab fracture line to the SSS that caught a portion of the slide, while Figure 6 provides a photograph looking uphill from one of the impacted SSS towards the crown of the slab. The entire Milepost 151 SSS installation was inspected during the summer of 2015, and while no visible damage to the frames was noted, the potential for a slide large enough to impart significant damage to SSS units exists. The proposed work would help to reduce this risk by locating the new SSU in the region where the above-described avalanche originated. Thus, this investigation will also improve the existing 151 SSS facility. It is noted that this region is adjacent to the SSS that is currently being monitored by InterAlpine Associates using instrumentation under a current WYDOT research contract.

One novel aspect of this proposed work is to evaluate the relative benefits of including a "fuse element" in series with the upslope ground anchor connection so that loads to the foundation are limited to a maximum known value. While the Swiss Guide is generally accepted as the *de facto* standard for generating forces due to creep and glide acting on an obstruction within a snowpack, there is some debate regarding the level of confidence with which these force effects can be calculated using the analytical expressions given in the Guide [3]. Therefore, with only one connection point to ground, it is prudent to either a) significantly overdesign the foundation system so that the probability of failure is extremely small, or b) limit the amount of force that can ever be imparted to the foundation via a yielding mechanism. It is this second approach that is of interest in this proposed work. By limiting the maximum force input to the foundation, damage to the foundation that would require significant repair can be avoided and yielded fuse elements can be replaced during summer seasons with simple hand tools.

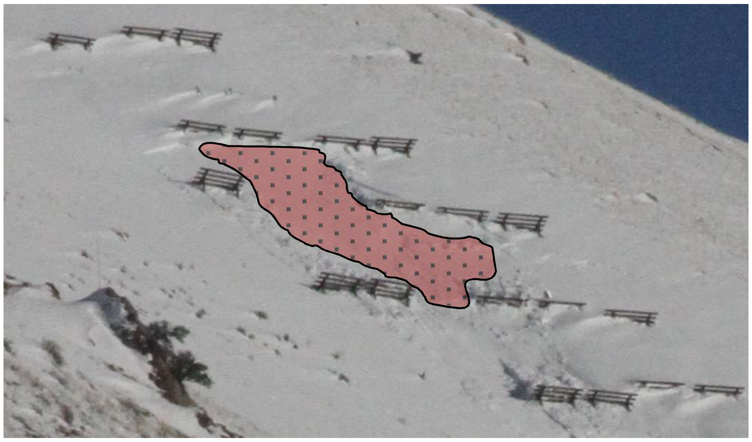

Fig. 4. Extents of small avalanche in upper reaches of the Milepost 151 site, January 2015.

Fig. 5. Avalanche debris resting on SSS at the Milepost 151 Avalanche site.

Fig. 6. Looking upwards from instrumented SSS towards fracture and crown of January 2015 slide at Milepost 151 site.

OBJECTIVES

The objectives of this proposed research project will be accomplished by the work items detailed in a later section. In an overview sense, the results of this project will provide the necessary background information that will describe the relative performance of SSU in their ability to effectively mitigate the risk of avalanche release from the starting zone. Additionally, the work will provide a framework for engineers that will help guide them through each step of the design process on future projects where SSU are utilized on a larger scale to minimize avalanche danger to motorists. The specific metrics by which the evaluation of the SSU will be measured include:

- Elimination of avalanches in the tile of snowpack at the upper reaches of the Milepost 151 site – visual observations.

- Relative ease of installation as compared to the rigid SSS installed at the site in 2012 – total time for fabrication and installation of SSU.

- Clear, reproducible design steps that can be adopted by others on future SSU projects.

- Effectiveness of a yielding fuse in series between a SSU and its ground anchor – visual observations of foundation deformation and measured strains in fuse element. It is stressed that if this aspect does not prove to be valuable or effective, this does not preclude the overall efficacy of SSU as a tool to mitigate risk.

- Cost effectiveness of SSU relative to rigid SSS – cost per hectare of retained snowpack. Cost comparison to include materials, fabrication, and installation.

Metrics related to improvements in WYDOT practices are focused on reduction or elimination of the need to actively manage a known avalanche path during winter season storms. The positive impact of use of SSU on this metric are somewhat binary in that if SSU prove to be an effective tool for essentially eliminating the need to monitor a slide area, then the result is the complete elimination of all costs associated with WYDOT winter maintenance staff and their hours spent attending to the particular avalanche site. Of course, the more important impact of a successful research outcome is the almost complete elimination of danger to the public adjacent to the avalanche zone.

BENEFITS

There are a number of potential positive impacts that may result from the study including:

- Creation of design guidance for SSU that can be used by WYDOT and other engineers. Currently, no design specifications for this type of system exist.

- Addition of new “tools” for avalanche risk reduction in the regions of Wyoming where avalanche danger to traveling public is present. Development of the SSU system may allow implementation of constructed starting zone defense at avalanche paths that were previously not a candidate for built systems due to their remoteness, size of starting zone (too large for rigid SSS to be cost-effective), or because of sensitive nature of the surrounding landscape (construction activities are reduced compared to rigid SSS).

- Elimination of the need for WYDOT personnel to manage avalanche risk during winter – the proposed system operates without input from avalanche forecasters and winter maintenance crews.

APPLICABLE QUESTIONS

By its very nature, research projects include uncertainty with respect to success of the new systems or methodologies being evaluated or developed. There are a number of potential difficulties that may be encountered during execution of this project, but it is anticipated that they can be addressed appropriately, as they arise. Potential obstacles include:

- Environmental review: the proposed test site has already undergone a NEPA review for the construction of the snow supporting structures, and it is not believed that an new environmental review will be required. The proposed SSU are less visibly intrusive than the SSS, and no significant visual impacts to the surrounding landscape are expected.
- Winter weather: successful evaluation of the SSU requires that they experience significant snow loading. If insufficient snow depths and/or climatic conditions occur during the proposed winter seasons of evaluation, a no-cost extension will be requested so that additional winter seasons of monitoring can take place.

STATEMENT OF WORK

This project will be completed using a three-task scope of work, and the following describes the specific scope of work proposed to complete each task. InterAlpine Associates has extensive experience in the type of work being proposed herein, including numerous past and/or current WYDOT research projects. Specifically, InterAlpine Associates has been involved in snow science and structural engineering related research for a combined 55+ years. Much of this work has been focused specifically on the problem of avalanche risk reduction, and InterAlpine Associates was responsible for the final design of the Milepost 151 SSS which have successfully eliminated the occurrence of large avalanches at the site that reach US89/191 on the valley floor below it. Moreover, the principal investigator has extensive experience in the design, installation, and use of the type of instrumentation being proposed to monitor the SSU.

Task One: Development of Design Criteria, SSU Geometry, and Design Procedure

Task One will involve the creation of design criteria, SSU geometry and connection details, and a generic design procedure to be used for site-specific designs in the future. This task will be performed in the first year of the project in between summers 2016 and 2017. InterAlpine will develop design criteria for SSUs that will address the following aspects of their design:

- Snow loading – expected to consist of guidance on use of the Swiss Guide to generate snow loads to due creep and glide forces as a function of site characteristics, and SSU geometry and configuration.
- Basic structural system layout – how different structural components are arranged and connected in order to create a surface that can support the snowpack effectively.
- Selection of type of structural members (materials, cross-section shape) and their connection details.
- Foundation design criteria and details.

Following the completion of development of design requirements, SSU units will be designed for a known avalanche path that is currently managed by WYDOT winter maintenance personnel and of WYDOT's choosing. However, it is proposed that WYDOT consider using the Milepost 151 Avalanche Site as the test site for SSU because: a) the site characteristics (snow depths, ground conditions, etc) are already known based on previous InterAlpine projects, b) all of the instrumentation required to conduct the SSU *in-situ* monitoring (as detailed under Task Three) is already in place on site and can readily be adapted for this purpose, and c) use of SSU at the Milepost 151 site can strengthen the operational functionality of the overall facility. The above information will be organized in a format similar to other United States transportation design standards (e.g. AASHTO) and that will be easily used by practicing engineers for implementation of SSUs.

Task Two: Fabrication and Construction of SSU & Instrumentation

InterAlpine will fabricate and install up to six SSU (as needed) at the test site during the summer of 2017. The SSUs will be flown in by helicopter. If the Milepost 151 site is selected, the SSUs will be located adjacent to existing SSS and where they can provide added support to the snowpack in the region where the small avalanche was observed in 2015. Each SSU will be connected to one ground anchor foundation, which is expected to consist of a steel helical ground anchor that can be installed by manual effort of crews without the need of powered equipment.

Instrumentation used by InterAlpine to monitor the Milepost 151 SSS, and that is already owned by WYDOT, will be utilized to experimentally monitor meteorological site parameters including snow depth and temperature, and to measure SSU structural deformations. This equipment is currently in use at the Milepost 151 site to monitor the performance of the SSSs but will be available for this proposed project by the summer of 2017. Most of the instrumentation currently deployed will be directly adaptable to measure similar, relevant parameters for the SSUs. Additional vibrating wire (VW) strain gages will be required and will be purchased for this project. Various additional mounting hardware and disposable supplies needed for installation of transducers will also be needed.

If the Milepost 151 site is selected as the test site for SSU, installation of the monitoring hardware will be very straight-forward. The equipment will be removed from the SSS it is currently affixed to, inspected and repaired (as needed), and re-installed on the new SSU. If a different test site is chosen, the instrumentation will be removed and packed off the 151 site and then re-deployed to the new SSU evaluation site.

Task Three: Data Collection, Analysis, and Implementation Recommendations

Data from the monitoring system will be collected over two winter seasons – 2017-2018 and 2018-2019. Data will be downloaded weekly and occasionally inspected to make sure all instrumentation is operating properly. After each winter season, analysis of the data will be conducted to evaluate response of the instrumented SSU. This includes snow depths, from which snow loads can be calculated by theoretical expressions for snow pressure as a function of snow density and depth. Vibrating wire strain gages will provide information on the material normal strains in components of the SSU, which then can be used to infer snow loads acting on the SSU. Strains in the yielding link described previously will be analyzed and will provide direct information on total snow load force acting on an individual SSU.

Visual inspection of the SSU during summer periods will provide valuable information on the interaction of the SSU units with the snowpack. Specifically, because SSU are connected to earth by one anchor point, there is the potential for rigid body motion of the SSU with respect to ground if snow loads are not directly along the fall line. It is expected that a SSU unit will rotate about its foundation connection to be aligned with the creep and glide motion of the snowpack, and this capability is indeed a benefit to the one anchor foundation. Other visual observations include overall movement of the SSU relative to its ground anchor should the yielding link reach its yield capacity.

Analysis of the data will proceed each winter season as it becomes available, and therefore this task is somewhat ongoing once the system is in place and winter conditions exist at the site. Each summer following a winter season, the data will be reduced and evaluation of the SSU performance based on the results will occur. Based on the observed performance (both visual inspections and data results), recommendations for implementation will be developed following winter season 2018-2019.

BUDGET

InterAlpine proposes to complete this three-task project on a lump sum by task, not-to-exceed basis, for $138,781 USD. A summary of the costs are presented in Table 1 and a detailed view by task is presented in Table 2.

Table 1 Summary Budget

INTERALPINE ASSOCIATES, LLC - SNOW SUPPORTING UMBRELLA PROJECT

Item	Cost
Task 1: Direct Labor Costs	$15,600
Task 2: Direct Labor Costs	$19,720
Task 3: Direct Labor Costs	$25,880
Subtotal of Direct Labor Costs	$61,200
Task 1: Nonlabor Costs	$0
Task 2: Nonlabor Costs	$71,530
Task 3: Nonlabor Costs	$6,051
Subtotal of Nonlabor Costs	$77,581
Total	**$138,781**

Labor Cost Summary		Principal Investigator	Senior Engineer	Technician	Subtotals/ Extensions
	Billing Rate:	$141	$95	$45	
Task 1 - Design		$7,050	$8,550	$0	$15,600
Labor:	**hours**	50	90	0	
				Task 1 Sub-total:	$15,600
Task 2 - Fabrication and Installation of SSU & Instrumentation		$6,345	$6,175	$7,200	$19,720
Labor:	**hours**	45	65	160	
Nonlabor Cost Summary:		Amount	QTY	Ext.	
Snow umbrella unit - six SSU		$4,600	6	$27,600	
Snow umbrella foundations - six SSU		$2,300	6	$13,800	
Vibrating wire strain gages		$160	24	$3,840	
Installation hardware and disposables		$1,400	1	$1,400	
Transducer wiring (feet)		$0.73	2400	$1,752	
Dry cell Battery		$110	2	$220	
Shipping of SSUs to Wyoming		$1,100	1	$1,100	
Helicopter support - materials to site		$7,000	2	$14,000	
Travel - Arizona to Jackson, WY (summer 2017)		$1,000	3	$3,000	
Per Diem (2 personnel, 22 person days, 1 summer)		$219	22	$4,818	
			Sub-total:	$71,530	
				Task 2 Sub-total:	$91,250
Task 3 - Data Collection, Analysis, & Design Recommendations		$14,100	$11,780	$0	$25,880
Labor:	**hours**	100	124	0	
Collect, Reduce, Review Data (2 winters)		40	100	0	
Visual Evaluations (8 hrs each of 2 summers)		0	24	0	
Develop Implementation Recommendations		60	0	0	
Nonlabor Cost Summary:		Amount	QTY	Ext.	
Travel - Arizona to Jackson, WY (summers 2018 and 2019)		$1,000	3	$3,000	
Per Diem (1 personnel, 3 days, 3 trips		$219	9	$1,971	
Cell phone charges for data collection ($45/month for 24 months)		$45	24	$1,080	
			Non-labor sub-total:	$6,051	
				Task 3 Sub-total:	$31,931

IMPLEMENTATION AND TECHNOLOGY TRANSFER

The results of this research will be documented in a final research reported submitted to WYDOT Research. The work being proposed will be used to develop recommendations on how SSU are to be designed, with detailed description of all applicable aspects that should be considered by WYDOT staff during the course of implementation of future projects utilizing the SSU technology.

Dissemination of the results of the proposed study is expected to be accomplished via the above described research report and by presentations at conferences that focus on an audience of avalanche risk mitigation and transportation planning. Additionally, it is expected that journal publications will be produced both during the period of research work and after the project is completed. Specifically, the following conferences are common venues for this type of work: Transportation Research Board (TRB) Annual Meeting and the International Snow Science Workshop (ISSW). Journals that focus on aspects of this study include: ASCE Journal of Cold Regions Engineering, Transportation Research Record (TRR), and Journal of Cold Regions Science.

The investigators have a very strong track record of successful publication of WYDOT research project results and have published three different manuscripts focused on results of their recent past or current WYDOT research projects.

REFERENCES

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DATA MANAGEMENT PLAN

Name of Researcher	InterAlpine Associates, LLC. / PI: Dr. Joshua T. Hewes
Name of Project	Design and Performance Evaluation of a Semiflexible Snow Barrier for Avalanche Protection
Funding Bodies	Wyoming Department of Transportation
Partner Organizations	None
Project Duration	30 months
Date Written	3/11/16
Date Revised	NA

1. INTRODUCTION

This project involves developing design guidance for a new type of snow supporting umbrella (SSU) to be installed in avalanche starting zones for the purpose of reducing the possibility of avalanche release and subsequent impact along transportation corridors. Additionally, a series of SSU will be fabricated and installed at the Milepost 151 Avalanche site near Jackson, Wyoming. Once installed, several SSU will be equipped with instrumentation to measure the *in-situ* response and efficacy of the units in reducing or eliminating the occurrence of large snow slab avalanches. The instrumentation will include an on-site data logger that will record various electronic signals from an array of transducers. This array will capture snow depth, temperature, and normal strains within the SSU. The data will be downloaded remotely via a modem that is interfaced with the data logger. The system will be powered by two deep cycle batteries which will be charged via solar panels.

Analysis of the data will yield useful information on how the test SSU respond to snow loading, and based on observed response, design recommendations for future SSU installations will be created.

2. DATA TYPE AND STORAGE

The primary data to be produced and stored includes measured physical parameters including depth of snow (inches), temperature of snow and air (degrees Celsius), and material normal strains (inch/inch), which are calculated based on conversion of electrical signals originating from calibrated transducers. The electronic signals are converted directly as the data is logged so that the data output files contain the above physical data in a format suitable for import into Microsoft Excel, or other similar spreadsheet software. Specifically, the data is recorded in a ".dat" file extension in ASCII format (text format). Data will be recorded hourly by the on-site data logger and will be downloaded weekly to InterAlpine PCs. InterAlpine backs up all project data from PCs to a backup storage hard-drive daily.

3. DATA ORGANIZATION, ACCESS, SHARING, AND PRESERVATION

InterAlpine utilizes a directory structure based on:

Client Name → WYDOT Project Number → Subfolder Name (e.g. "Logged Data *Year*", "Data Analysis", "Project Administration", etc.)

No special restrictions on data access are anticipated by InterAlpine. Only InterAlpine staff has direct access to the PCs storing the data, but other researchers could be granted access to the original data files after completion of the research project and with WYDOT's approval. Potential users include other snow science researchers and engineers, WYDOT personnel, or other government officials with interest in the outcomes of the study. InterAlpine Associates, LLC and WYDOT possess joint ownership of the data.

Data is stored digitally on hard-drive equipment owned and maintained by InterAlpine Associates. Data is recorded in a file format that is expected to have no "shelf life" as long as the hard-drives are stored in a climate controlled and indoor environment.