ABSTRACT: Despite increasing traffic volumes and all-weather travel demands on the mountain roads of the Western United States, surprisingly few examples of constructed passive avalanche defense exist. Active avalanche hazard management techniques require significant personnel resources to implement; can be ineffective; are undesirable adjacent residential development, recreation areas, and critical wildlife habitat. Passive defense measures on the other hand, used extensively in Europe, provide avalanche hazard reduction without requiring personnel in-the-loop, a resource in short supply during storm fighting periods and attendant high avalanche hazard. Presented is a design and deployment configuration for starting zone snow supporting structures at the Milepost 151 Avalanche above US89/191 in Jackson, Wyoming. The Swiss Technical Guideline was utilized along with domestic structural/geotechnical engineering design criteria. A novel deployment configuration was developed, focusing on the National Environmental Policy Act’s (NEPA) visual retention requirements. A collaboration between the Forest Service’s landscape architect, and experts from the Wyoming DOT and their contractor was utilized. The resulting configuration differs dramatically from the orderly deployments typically found in practice. The arrangement of snow supporting structures mimics visual elements of the existing landscape, leading to an “organic” appearance that has the potential to retain the visual characteristics of the site.

KEYWORDS: avalanche, hazard, mitigation, passive, snow bridge

1. INTRODUCTION

As a consequence of urbanization and increased traffic, the hazard to motorists from an active avalanche path at milepost 151 on US 89/191 has also increased. US 89/191 is the primary regional trunk road into and out of Jackson, Wyoming, which is located less than one mile north of the 151 Avalanche. The road was widened from two to four lanes in 1998, and the average daily traffic volume has increased 700% from 1970 to 2007 (Yount 2008). Figure 1 is the WYDOT Avalanche Atlas depiction of the 151 Avalanche.

The 151 Avalanche avalanches by direct action during periods of heavy snow and strong southwesterly winds, and can avalanche by delayed action in seasons when depth hoar is present at the ground surface. US 89/191 is located at the valley floor 348 m vertically below the 151 Avalanche starting zone. On average, the 151 Avalanche avalanches to the road 1.5 to 2.0 times per year. In the past, a fraction of these avalanches have impacted motorists’ vehicles on the roadway. To date, there have been no loss-of-life incidents.

The hazard at the 151 Avalanche has been addressed with limited success by the deployment of snowpack disrupting snow sails (Decker, 2005). The Wyoming Department of Transportation (WYDOT) continues to address the 151 Avalanche with conventional forecast and active control measures, typically during heavy snow periods when WYDOT personnel resources are at a premium and the regional surface transportation system is already taxed. Moreover, the 151 Avalanche starting zone is managed as critical big game winter habitat and the adjacent South Park area of the Jackson Hole valley is now developed. Hence, regular use of explosives is not compatible with these other uses.

An optimal solution for avalanche hazard management at the 151 Avalanche is an effective passive (constructed) system that performs “stand alone” and does not require WYDOT winter
maintenance personnel consideration during storm fighting periods. There are three constructed avalanche hazard reduction technologies applicable to the 151 Avalanche. Each is an order of magnitude more expensive than the former:

1. Wind/snow disrupters (snow sails) in the avalanche starting zone.
2. Snow supporting structures (snow bridges and rakes) in the avalanche starting zone.
3. Snow (avalanche) shed or gallery at the road.

The snow sail deployment at the 151 Avalanche was an attempt to address the avalanche hazard with a cost effective constructed solution. It has been of limited success in reducing avalanche occurrence, especially during periods of intense snow and wind. A snow shed or gallery (an artificial tunnel) at and over the highway is not a cost effective solution, exacerbated by the expansion of US 89/191 from two to four lanes at the point where the 151 Avalanche path crosses the roadway. Additionally, the act of passing the avalanche over the roadway and onto adjacent private land poses an entirely new suite of issues.

The next logical escalation in efforts to reduce the avalanche hazard at the 151 Avalanche was to explore the design, costs, and USDA Forest Service administered National Environmental Policy Act (NEPA) requirements for a deployment of snow supporting structures in the 151 Avalanche starting zone.

Snow supporting structures are a form of constructed defense in the avalanche starting zone that holds the snow statically in place and precludes the onset of avalanching. They operate independently and do not require winter maintenance personnel resources to perform their function during storm fighting periods. They are not novel. Dating from the late 1950’s and early 1960’s, they have been used extensively in Europe and Asia. The standard-of-practice for the site specific design of snow supporting structures is “Defense structures in avalanche starting zones Technical guideline as an aid to enforcement” or the “Swiss Guideline” (FOENWSL, 2007). The efforts reported here for the design of snow supporting structures for the 151 Avalanche utilize the Swiss Guideline, but also implement domestic structural engineering criteria and practices as the basis for the resulting final design.

2. SNOW BRIDGE DESIGN FOR THE 151 AVALANCHE

2.1 Design Specifications

United States domestic experience in the design and implementation of snow supporting structures for mitigation of avalanche hazard in transportation applications is limited. Whereas in-depth national specifications for the design of bridges, highways and other transportation facilities have been around for decades, no federal requirements or guidelines for design of snow bridges or rakes exist. The preeminent treatise on the implementation of snow supporting structures for avalanche hazard mitigation is the Swiss Guideline. Although this is a fully mature and comprehensive design guideline, it does not prescribe all aspects of design of snow bridges. Furthermore, it references European design and material specifications which are not necessarily appropriate or applicable in the US. Thus, the Swiss Guideline serves as an invaluable starting point for the development of the American “voice” for the design of snow supporting structures, but the resulting design for the 151 Avalanche is not a simple importation of the European snow bridge.

US structural design specifications were used for the 151 Avalanche and include: Building Code Requirements for Structural Concrete (American Concrete Institute, 2005), Specification for Structural Steel Buildings (American Institute of Steel Construction, 2005), Manual for Design and
2.2 151 Avalanche Snow Load Environment

The primary loads to be resisted by snow supporting structures consist of the down slope component of the snowpack’s weight and the loads that result as a consequence of the snowpack’s slow, viscous deformation under its own weight. These latter loads include the motion between the snowpack as a whole and the ground surface (glide) and the internal deformation of the snowpack (creep). They are accounted for in design through the application of an equivalent static load, expressed as a fraction of the static snowpack weight. The snowpack weight is based on the design snow depth which is defined in the Swiss Guideline as that with a recurrence interval of 100 years. Whereas the Swiss and other European countries have recorded snow depth measurements for up to seven decades, no recorded snowpack depth information was available for the 151 Avalanche. Thus, the design snow depth was selected based on anecdotal evidence from WYDOT and the nearby Snow King Resort, and was taken as 2.0 m.

Snowpack glide and creep are a function of the ground surface roughness characteristics, solar exposure, and snow density. In the Swiss Guideline, the influence of glide on structure loads is accounted for by multiplying the down slope component of the snow weight by a glide factor, \( N \). At the 151 Avalanche, the ground consists of primarily smooth grass and the slope is facing west-southwest, both of which contribute to a high tendency for glide. Based on the Swiss Guideline, a glide factor of \( N = 3.0 \) was selected, which implies total snow loads three times larger than that due to weight of the snow alone. The component of snow weight that acts parallel to the slope and that is resisted by the snow supporting structure is calculated based on the slope inclination, \( \psi \). The maximum slope over the starting zone at the 151 Avalanche is 35°.

Additional considerations in the calculation of total snow loads are the boundary conditions at either end of the snow bridge (across slope). If a snow bridge is positioned in the snowpack a significant distance from other snow bridges, the glide and creep of the snowpack around the end of the structure imparts larger loads to the structure than if it were of infinite width (across slope). These increased loads are termed “end effects”. Based on the Swiss Guideline and a snow bridge separated from adjacent bridges by more than 2.0 m, an end effect factor, \( f_e = 4.75 \) was calculated for the 151 Avalanche. This factor increases the down slope snow loads (snowpack weight plus glide and creep effects) in a discrete end-effect region at the side of the snow bridge grate.

2.3 Snow Bridge Unit Design

Traditional European design of snow bridges is based on linear and continuous rows of structures separated by a given distance in the line of slope and distributed over the avalanche starting zone. This orderly arrangement, although attractive from a structural engineer’s pursuit of efficiency and cost considerations, was not acceptable for the 151 Avalanche based on the visual attributes of the deployment configuration (discussed in detail in a following section). Because of this, design of a single, stand-alone snow bridge unit was pursued. This “unit design” was developed so that it can be used anywhere in the deployment configuration irrespective of whether it is grouped with other units or whether it is an isolated single unit. The primary advantage of this approach is simplicity in the design, fabrication, and construction stages. Another significant driver for the unit design was the desire to minimize construction effort on the steep slope by allowing an entire (fully assembled) unit to be transported via helicopter and lowered into position on the slope.

The Swiss Guideline is not a “cookbook” for snow bridge design where all dimensions, member sizes, connections details, etc. are given by a simple “recipe”. In fact, it explicitly states that “The present guideline allows considerable leeway in laying out and dimensioning the structures.” What follows is a brief summary of the process by which the characteristics of the 151 Avalanche snow bridge unit were selected.

A side elevation view of the snow bridge unit is given in Figure 2. The unit consists of two girders to which crossbeams are connected – this forms the grate which supports the snowpack. Connected to the girders are struts that support the grate and that connect to lower foundations downhill from the grate. The length from the top of the girder to the ground, measured along the axis of the girder, is set such that the vertical height of the snow bridge equals the design snowpack depth, \( H_c \). No recommendation is given in the Swiss Guideline on where along the girder length the strut should attach. The 0.66 m from the top of
girder to the strut attachment point was
determined based on a consideration of balancing
the girder negative internal moment demand at the
strut attachment point with the positive girder
moment demand in the span between the strut
attachment point and the foundation.

A consequence of the unit design
approach was the need to limit the weight of the
unit so that it could be safely handled by
commonly available helicopters. With the height of
the snow bridge selected as previously described,
the width as measured across the slope along a
contour became a critical variable. Preliminary
engineering of the snow bridge unit indicated a
maximum grate width of 3.658 m in order to
comfortably meet lifting weight limits. Figure 3
shows a drawing of the snow bridge viewed
downhill and perpendicular to the grate surface.

Figure 3: Downhill and perpendicular view of snow
bridge grate

The distance between the end of a
crossbeam (side of grate) and the girder is not
addressed in the Swiss Guideline. This
“overhang” length was selected with consideration
of the different distributed snow pressure patterns
acting on the grate. Because some units will be
isolated (separated by say 10 or so meters from
other units) while others will be grouped in a line
across the slope, the unit must be designed to
accommodate any of the various snow pressures
that can occur. A unit that is in the middle of three
units placed together in a line for example will not
experience the increased loading due to end
effects. For this uniform pressure distribution, a
given optimal crossbeam overhang length could
be determined. However, for units that have a side
not bounded by another unit, end effects are
significant and the crossbeam experiences greater
snow pressures at its free end than along most of
its length and away from the end effects. A
different optimal overhang length could be
determined. The term “optimal” means that
efficient use is made of the structural steel section,
which in turn means that local maximum internal
moment demands along the crossbeam are similar
(or equal). Thus, for the 151 Avalanche, the
crossbeam overhang length was chosen so that
the maximum positive crossbeam moment in the

Figure 2: Side elevation view of snow bridge unit
design on cast-in-place concrete foundations

The Swiss Guideline recommends that
girders be laid downhill 15° from perpendicular to
the slope. The angle between the strut axis and
the slope however is not mentioned in the Swiss
Guideline and thus an analysis of the influence of
this angle on foundation forces and strut axial
force was conducted. From a structural engineer’s
perspective, it is obvious that as the strut-to-slope
angle (interior angle between strut and slope)
becomes larger, the distance between the upper
and lower foundations becomes smaller with the
consequence of increased foundation forces (to
satisfy rotational equilibrium). Since large
foundation forces require more robust foundations,
“large” strut-to-slope angles are undesirable. The
impact of reducing the strut-to-slope angle is that
distance between foundations becomes greater
which leads to lower foundation forces. However,
this also leads to a longer strut length which can
be problematic based on unbraced length and
compression member buckling (stability)
considerations. In the end the 45° angle selected
provided a reasonable balance between the
opposing needs of minimizing foundation forces
and minimizing the strut unbraced length.
span between girders and for the case of a uniform snow pressure pattern was equal to the negative crossbeam moment at the girder and under the non-uniform snow pressure pattern associated with end effects. The optimal overhang of the crossbeam expressed as a fraction of the total grate width was 0.15. Note that because the magnitude of end effects depends on the arrangement of units (across slope spacing) and glide factor, both of which are unique to a given site, the optimal crossbeam overhang length will be different for other avalanche defense projects.

The spacing of crossbeams along the height of the grate was selected based on recommendations in the Swiss Guideline, which provides a range of acceptable openings in between individual crossbeams.

2.4 Snow Bridge Foundations and Construction

The ground conditions at the 151 Avalanche vary from rock outcropping to areas with several feet of soil. The Swiss Guideline suggests that several different foundation types may be used including cast-in-place concrete foundations, prefabricated foundations, micropiles, and ground anchors. However, it states that the preferred method of connecting snow supporting structures to the slope is via micropiles (a soil nail in compression) and anchors (a soil nail in tension). This approach was used for the 151 Avalanche and all units will have foundations that utilize ground anchors. The distinction between a soil nail in compression versus tension is not made by the authors in this work, and the term “ground anchor” is used to describe a soil nail whether in compression or tension.

The desire to simplify construction and the corresponding plan to install fully assembled units via helicopter significantly influenced the selection of foundation type and connection details. Because heli-tac can be expensive, an efficient (quick) method of securing a snow bridge on the slope after being lowered into position was needed in order to minimize total airtime and thus costs. Another key issue in the development of foundation connections was the need to provide for reasonable tolerances for the installed location of ground anchors. An initial connection system was thus developed that allows for both angular and linear dimension errors in location of ground anchor bars. The connection also provides for rapid capture and securing of a snow bridge as it is lowered into position on the slope. Figure 4 shows a detail of the strut foundation, which consists of the ground anchor bar, a series of steel plates, steel anchor rods and nuts, and poured in place concrete. The construction process is envisioned as follows. All ground anchors are installed and then soil is excavated around each for the concrete footings. A spherical nut is installed on the ground anchor bar, and a steel plate with a hole cut out at its center ("Plate A" in Figure 4) is lowered onto the nut. The 19mm diameter ASTM F1554 anchor rods and Plate B (see Figure 4) are attached to the strut base plate before the snow bridge is lifted from the staging area. Plate B has a 146mm diameter hole cut out at its center, and the ground anchor bar has a diameter on the order of 25mm. As the snow bridge unit is lowered into position on the slope, ground crews guide each ground anchor bar up through the center hole in Plate B. When the weight of the unit is resting completely on the ground anchor bars via contact between Plate A and Plate B, Plate C is lowered onto the ground anchor bar and finally the top spherical nut is installed. The tolerance for misalignment of ground anchors is provided by the difference in diameter of the hole in Plate B and the ground anchor bar. Thus, a tolerance of 60mm from ideal center in any direction for each ground anchor bar is provided. Height adjustments can be made via the spherical nuts and ground anchor bars as well as by the steel 19mm diameter anchor rods and associated nuts. A similar foundation connection detail is used at the girder (uphill) foundation.

Figure 4: Strut concrete footing foundation and connection detail for sites with adequate soil cover.
The foundation and connection to the snow bridge described previously allows for reasonable misalignment of ground anchors while also providing for fast installation. However, where soil over rock in the 151 Avalanche starting zone is thin, making excavation for the concrete footing difficult, different snow bridge foundation connections are required. Figure 5 shows the strut (downhill) foundation system which utilizes one ground anchor to secure each strut. The strut connects to the foundation via a pin and shackle type connection. A shackle built from steel plates and a bar coupler is installed onto the ground anchor bar. A steel plate welded to the bottom of the strut is fastened to the anchor bar shackle via a 32 mm diameter steel pin.

Because the strut carries large axial compression loads (on the order of 65 kN) and since perfect alignment of the strut and ground anchor axes is likely not to occur, an additional structural element is required to connect to the strut and ground anchor. This element connects the downhill and uphill foundations and ensures that the strut ground anchor is not overloaded due to off-axis or transverse loading. Figure 6 shows a side elevation view of a snow bridge unit to be used where rock prevents installation of the concrete footing foundation. The girder foundation uses two ground anchors and a connection similar to that used at the strut base. These foundation connections will require very tight control of the installation location of each ground anchor and thus will require greater construction effort. However, it is believed that by use of a "jig" or template on the slope during ground anchor installation, successful installation of fully assembled snow bridge units via heli-tac support can be accomplished.

3. SNOW SUPPORTING STRUCTURE DEPLOYMENT CONFIGURATION

3.1 Deployment Criteria and Configurations

Structures for avalanche defense support a portion of the snowpack equal to their across slope width and an uphill zone of influence. The length of this zone of influence uphill from any given snow bridge is a function of the same parameters that control the structural design, and is dominated by the design snow depth and slope angle. For the 151 Avalanche this length is 15.24 m.

The 151 Avalanche starting zone is approximately 274 m long (up/down slope) and has an average width of 18.3 m laterally for a net area of 5014 square meters or 0.50 hectares. The snow bridges in the 151 Avalanche starting zone are to be implemented as single units that are 3.658 m wide laterally and hence support a “tile” of snowpack 3.658 m wide and 15.24 m in length, or as double units separated by a 0.305 m gap for a net lateral effective width of 7.62 m, or as triple units with a resulting effective lateral width of 11.58 m. Though supporting a slightly wider tile of the snowpack, double and triple units are limited, in the same fashion as single units, to an uphill
effective length of 15.24 m. Based on this geometry and the areal extent of the 151 Avalanche, it will take approximately 70 unit snow bridges, in various combinations of singles, doubles and triples to adequate cover, and support the 151 Avalanche snowpack in place.

Despite being valuable information, the resulting number of 70 snow bridges in the 151 Avalanche starting zone says little about where, exactly, they are to be placed and the resulting cumulative appearance they’ll have once they are installed. Moreover, the appearance of a deployment of snow bridges in the 151 Avalanche starting zone is not a trivial matter. The appearance of 70 snow supporting structures in the 151 Avalanche starting zone can be dramatically different, depending on the configuration chosen for their deployment.

The 2007 Swiss Guideline suggests four different snow supporting structure deployment configurations. Nevertheless, each of these results in a relatively orderly and repeating pattern of snow structures in landscapes where these patterns are not found naturally. For this reason, deployments of snow supporting structures tend to have high visual impacts on the landscape, especially as seen from a distance.

3.2 Organic Deployment Configuration

The National Environmental Policy Act (NEPA) dictates that activities and facilities on Federal lands must minimize or mitigate their impacts on the environmental assets of that site. The list of potential environmental assets is daunting and the process of identifying them and recommending various mitigation measures are Environmental Assessments (EA) or Environmental Impact Statements (EIS).

In the case of the 151 Avalanche, the Bridger-Teton National Forest conducted an EA for the snow sails, which are now installed in the 151 Avalanche starting zone. The visual attributes of the 151 Avalanche starting zone was the only environmental asset identified as being potentially impacted. The NEPA mitigation criteria for this attribute is known as visual retention. The visual attributes of the site found prior to construction must be retained or restored after construction.

A collaborative work-process, utilizing expertise of the Forest Service landscape architect and avalanche experts from WYDOT and its contractor, was put in place for the purpose of assuring that a deployment of snow bridges in the 151 Avalanche starting zone would both retain the visual characteristics of the site and perform their technical task of avalanche defense. Using suites of single, double and triple snow bridges, and the paired and triple clusters of small conifers found as visual elements in the adjacent landscape, the 151 Avalanche snow bridges were deployed in an organic configuration. The resulting deployment configuration is shown in Figure 7. It is dictated by the appearance of the surrounding landscape and actual landform, and the motion of the wind over the 151 Avalanche starting zone.

3.3 Reforestation

When the 151 Avalanche snow bridge deployment is coupled with reforestation, the potential to retain the visual attributes of the site is greatly enhanced. Figure 8 shows the 151 Avalanche snow bridge deployment with reforestation in the creep protected zone immediately below a given snow bridge. Though conifer reforestation assists in retaining the visual attributes of the 151 Avalanche starting zone, it will not replace the snow bridges as an avalanche defense measure. The density of mature conifer stands in the surrounding area is not sufficient to preclude the onset of avalanches.

4. 151 AVALANCHE SNOW BRIDGE COST ESTIMATES

Cost estimates to fabricate, ship, transport and installed 70 snow bridges in the 151 Avalanche starting zone is on the order of $1.2 million US dollars. These net present costs can and will be influenced by today’s very volatile material and construction cost environment and could escalate rapidly. The one-time and fixed costs are amortized for an installation of 70 structures. The net unit cost per snow supporting structure installed in the 151 Avalanche starting zone is $16,600.0 US dollars.
Figure 8: A virtual rendering of snow supporting structures with reforestation in the 151 Avalanche starting zone in a configuration that retains the visual character of the site

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