SNOW PRESSURES ON A RIGID SNOW SUPPORTING STRUCTURE AT THE MILEPOST 151 AVALANCHE, JACKSON, WYOMING
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ABSTRACT: Mitigation of avalanche hazard to roadways within the Western United States has historically been conducted by means of artificial release of explosives at the starting zone or by firing of artillery at it, while the road is temporarily closed. Newer to the U.S. are management strategies that look to mostly eliminate the potential for natural avalanches by holding or retaining the snow pack in place with constructed defense systems such as snow bridges or snow nets. The Wyoming Department of Transportation (WYDOT) has embraced constructed defense technology and installed 87 snow supporting structures – specifically snow bridges – at the Milepost 151 Avalanche in Jackson, Wyoming, and this system has eliminated the large natural avalanches that previously reached US Hwy 89/191 at a frequency of once or twice per year. A research project to monitor site snow parameters including temperature and snow depth, and to experimentally measure structural response parameters of one snow bridge has been underway since 2014. Thirty-three different transducers were installed at the site and these include vibrating wire pressure cells, vibrating wire strain gages, ultrasonic snow depth sensors, and thermistors. This paper describes the results of this research project including: spatial variation of snow pressure across the width and height of the snow bridge, temporal variation of snow pressure over the winter seasons 2014-2015 and 2015-2016, and a comparison of measured snow pressures with theoretical pressures predicted by the Swiss Guide and by other researchers.

KEYWORDS: Avalanche, Snow Supporting Structures, Mitigation

1. INTRODUCTION

Snow supporting structures have been used for many decades in Europe and more recently in the United States to arrest the movement of snowpacks that have the potential for avalanching onto developed areas in mountainous regions. One critical aspect in the design of such structures is the accurate estimation of snow pressures acting on a structure installed in the snow field, or avalanche starting zone. Internal creep deformations under gravity and glide movement of the entire snowpack with respect to the ground contribute to snow pressure, and there have been many attempts by others to quantify snow pressures using avalanche site characteristics including maximum expected snow depth, density, and temperature, and ground slope angle and surface roughness (Bader et al. 1939, Haefeli 1948, Salm 1977, MClung 1993). Formal codification of equations for snow pressure calculation has been done by researchers from Switzerland based in part on the work by Haefeli (1948), and the “Swiss Design Guide” for snow supporting structures is used by practicing engineers world-wide for the design of constructed avalanche defense systems (Margreth, S. 2007).

This paper presents the results of a research program whose aim is to measure experimentally snow pressures exerted on a rigid snow supporting structure and to compare these with the analytical snow pressure equations developed by others and with those used in the design of the deployment. Additionally, of interest is the variation of snow pressures with snow depth, and also laterally along a contour line where structure boundary conditions can influence the magnitude of snow pressure effects. Changes in snow pressures throughout a winter season as the snow densifies and the daytime high temperatures vary is also of particular interest.

The instrumented “snow bridge” is one of a total of 87 snow supporting structures (“SSS”) installed at the Milepost 151 Avalanche Site near Jackson, Wyoming, USA. The starting zone is located...
approximately 300 m above U.S. Hwy 89/191, which serves as a major regional trunk into the Jackson Hole area from the south. The system of SSS was installed in the summer of 2012 and instrumentation to monitor snow pressures was installed in the fall season of 2014.

2. DESCRIPTION OF SITE AND SSS DEPLOYMENT

The instrumented SSS is located at an elevation of approximately 2,150 m A.S.L on a west – southwest facing slope whose topographic features lead to wind deposited snow slabs. Prior to installation of SSS at the site, snow slabs large enough to produce avalanches onto the highway released naturally at a frequency of once or twice per year. The SSS analyzed in this investigation sits near the top of the starting zone region where the ground slope is approximately 37 degrees, and the ground surface consists of soil with native grasses and scree with sizes ranging from a few centimeters up to 20 centimeters. During engineering design in 2010, the deployment of individual SSS throughout the starting zone was carefully selected so as to adequately provide support to the snowpack but also so that an “organic arrangement” of SSS units that blends visually into the surrounding landscape was obtained (Hewes et al. 2010). Rather than long continuous rows of SSS being used, as is the common practice in Europe, individual SSS units are distributed across the starting zone as either single units, or double or triple units arranged side-by-side. Lateral spacing between grouped units is approximately 1 m.

The design vertical snow depth for the site is 2.0 m which results in a SSS height, measured perpendicular to ground, of 1.64 m. Individual SSS units are 3.66 m in width and consist of structural steel tube crossbeams connected to wide-flange girders and tube-shaped struts (see Fig. 1). Weathering steel is used throughout the SSS, and SSS units are pinned with high-strength bolts at their bases to micropile foundations. The grate surface is laid downhill 15 degrees from a normal to the slope. The instrumented SSS is an outside unit of a three SSS unit grouping, with the next adjacent unit being approximately 4.75 m along the contour away (see Fig. 2). Thus, the unit being studied is subject to “end effects” which are a result of unrestrained downhill movement of the snowpack around the free SSS edge. The upslope distance between the instrumented SSS and the next row of SSS is approximately L=14 m.

3. BACKGROUND

3.1 Overview

Design of the experimental program was guided by the desire to assess and characterize the snow load environment for a rigid SSS placed within a snow field in an avalanche starting zone. The basic processes leading to downslope snow pressures on a structure include internal deformations within the snowpack depth due to visco-elastic response of snow – creep – and rigid body type motion of the entire snowpack downslope – glide. Numerous parameters or conditions will influence the magnitude of snow pressures acting on a rigid obstacle placed in a sloping snowpack, and these include: snow height, density, and temperature, slope angle, ground surface roughness, solar aspect, and structure boundaries in the dimension parallel to a contour line (width direction). Presented below is a brief description of these parameters and how they are expected to affect snow pressure intensity.

3.2 Depth and Density of Snow

Slope parallel snow pressures will increase with increasing height of snow since vertical stress varies proportional to \( \rho g H \), where \( \rho = \) density, \( g = \) gravity and \( H = \) height. Previous work by others (Salm 1977), has shown a variation of snow pressure with depth that resembles a parabolic curve, with zero stress at the free snow surface and increasing to a maximum and then reducing nearer to the ground. It is noted that predictive equations for snow pressure provide an average snow pressure, \( \sigma_{ave} \), that is assumed over the full depth of snow, i.e. a uniform pressure. Density is expected to increase over the winter season as the snowpack settles, and although density will vary within the depth of snowpack, averaged quantities are generally used in predictive equations.

3.3 Temperature

The biggest influence of temperature on snow pressure is that associated with snow gliding. Others have documented (McClung and Larsen, 1989) that gliding occurs when the ground surface temperature climbs above freezing and water is present at the snow – ground interface. This condition is expected during the early spring when daytime high temperatures are consistently above freezing and the snowpack “unlocks” from the ground surface. Also expected are daily variations in pressure during the warming springtime period.
as the snowpack releases during late afternoon warm periods and then “locks” as temperatures drop below freezing at night.

3.4 Boundary Conditions Along Contour

Snow pressures exerted on an infinitely wide SSS placed in a snow field are expected to differ significantly compared to a single SSS of finite width in the same snowpack. This is most easily described using an analogy of water flowing in a stream around an object (large boulder) in the center of the stream – the water is able to flow around the object. In the same manner, snow that is creeping and gliding downslope is able to move past a fixed structure in its path on either side of the structure. This induces additional pressures that are termed “end effects” since they occur in the vicinity of the ends, or free edges of a SSS. In this research program, because long continuous rows of SSS are not used, end effects are expected to be present near either side of the SSS being studied. The edge of the SSS with 4.75 m distance to the next adjacent unit is expected to experience larger end effect pressures than the edge with 1.0 m lateral distance. Swiss Guide predictive equations for snow pressure account for end effects using an “end effect factor”. Away from the free edges, the snow pressures interior to the instrumented SSS are expected to be much smaller.

4. INSTRUMENTATION

The array of transducers used to monitor various snowpack parameters and SSS structural response includes:

- 20 vibrating wire pressure cells
- 3 ultrasonic snow depth sensors
- 30 thermistors for temperatures
- 10 vibrating wire strain gages

Twenty Geokon model 4800 vibrating wire pressure cells (PCs) are mounted along the height and width of the instrumented SSS to monitor snow pressures normal to the SSS grate surface, which is comprised of the five horizontal steel cross beams (see Fig. 1). The PCs, which have a full scale measurement range of approximately 70 kPa, are arranged in a rectangular array with five rows along grate height and four columns across the SSS width. The first (c1) and last (c4) columns of PCs sit at the outside edges where end effects may be present while the two interior columns of PCs are spaced at intervals of 1.22 m inwards from the crossbeam ends.

Because other researchers (McClung et al. 1983) have experienced difficulties in using pressure cells to reliably or accurately measure snow pressure in wet snowpack, the vibrating wire strain gages are mounted at locations on the SSS that will allow determination of total resultant slope-parallel snow force acting on the unit. From normal strains in the steel struts, girders, and drag struts, axial (normal) forces can be determined and static equilibrium can be used to calculate the location and magnitude of the resultant snow force. This resultant force can then be compared to the that calculated from PC data by integration of pressures over the height of SSS. Figure 3 shows locations of strain gages while Figure 4 shows a photograph of the instrumented SSS unit.

Thermistors are used to monitor temperature at every transducer mounted on the SSS. For all transducers, data is logged hourly using a data acquisition system that is described more completely by Hewes et al. (2016).

![Fig. 1: SSS with pressure cell numbering scheme](image1)

![Fig. 2: Instrumented SSS at Milepost 151 Site](image2)
5. EXPERIMENTAL RESULTS

A portion of the experimental data collected from winter seasons 2014-2015 and 2015-2016 has been analyzed and subsequent sections provide a discussion of the most salient features of the results. This includes snow pressures measured via PCs, snow depth, and temperature. Yet to be analyzed and with details forthcoming in another publication, are structural steel strains that will help generate total snow forces acting on the SSS. These will be used as a check on directly measured snow pressures (PC data).

Snow densities for each winter season were determined by correlation of field measurements adjacent to the instrumented SSS with those from a nearby SNOTEL site located at a similar altitude and with the same west facing aspect. Table 1 provides data for snowpack density over the two winter seasons discussed in this paper.

<table>
<thead>
<tr>
<th>Year</th>
<th>Jan</th>
<th>Feb</th>
<th>March</th>
</tr>
</thead>
<tbody>
<tr>
<td>'14-'15</td>
<td>369</td>
<td>396</td>
<td>450</td>
</tr>
<tr>
<td>'15-'16</td>
<td>279</td>
<td>339</td>
<td>398</td>
</tr>
</tbody>
</table>

5.1 Snow Pressure versus Time

Recorded vibrating wire PC data includes changes in internal fluid pressure due to thermal effects (expansion/contraction of steel pressure cell plate and/or SSS), barometric pressure changes, and the applied snow pressure. In order to obtain data that only represent snow pressures, the thermal and barometric pressure effects were removed from all recorded signals for the 2014-2015 and 2015-2016 winter seasons. With these effects mitigated, one expects a zero pressure signal for all PC locations located above the snowpack. This is indeed mostly the case for all twenty PCs, and for brevity, only pressure versus time from PC4 and PC20 are presented. Figures 5 and 6 present plots of snow depth, snow temperature, and snow pressure for PC4 and PC20 for the 2014-2015 and 2015-2016 winter seasons, respectively. Both figures present data between late December when significant snow accumulations began to mid- to late-March.

In Figure 5, the measured snow pressure for PC4 (located in column 1 – see Fig. 4, 4th from top row – see Fig. 1) is approximately zero until a significant snowfall event on about January 4th. However, snow pressure remains small at just under 5 kPa even after additional snowfall, with a maximum snowpack height of just over 1.75 m for the season. Immediately following the last major snowfall event of the season on February 2nd, a marked warming period began and the daytime snowpack high-temperatures at PC4 reached 5 ºC or above for a period of several weeks (it is noted that snowpack temperature closer to the ground at PC5 reached similar daytime highs). During this period snowpack height began to decrease but snow pressure on PC4 increased markedly, reaching as high as 35 kPa on February 25th. The diurnal variation of temperature and the corresponding fluctuation of snow pressure is clearly visible, and the spikes in pressure correspond to the warmest daily snowpack temperatures of late afternoon. Conversely, the decreases of pressure occurred when daily temperatures reached their lowest values, which were significantly below freezing. The data clearly
illustrates the snowpack gliding phenomenon where release of the entire snowpack from the ground upon thawing leads to marked increases in down slope snow pressure.

Data from PC20 during 2016 shows trends similar to that detailed for PC4. Snow pressure at PC20 remained small under the influence of only snowpack creep, i.e. absent of temperatures above freezing and the corresponding glide phenomenon. In mid-February snowpack temperature at PC20 increased to 0 °C and a corresponding uptick in pressure is seen on about 2/17. Then again in late February a prolonged warming period existed with snowpack temps at or above freezing and measured snow pressures increased significantly.

5.2 Snow Pressure versus Height

Maximum snow pressures recorded for 2014-2015 and 2015-2016 seasons have been analyzed and Figures 7 and 8 illustrate the distribution of slope parallel snow pressure within the snowpack depth. Z is height of a PC measured normal to the slope while H is snowpack height measured in the same fashion. Pressures are grouped by columns of PCs where “column 1” corresponds to PCs 1 to 5, “column 2” to PCs 6 to 10, etc. (see Figs. 1 and 4). Columns 1 and 4 correspond to the edges of the SSS, where column 1 is immediately adjacent to another SSS and column 4 is on the edge of the SSS with 4.75 m spacing to the next SSS. Columns 2 and 3 are the two interior columns of pressure cells.

With reference to Figure 7, as expected, maximum pressures exerted on PCs in column 1 and 4 are significantly larger than those near the interior of the SSS (columns 2 and 3) and away from end effect loading. Surprisingly, pressures at column 1 are greater than those in column 4, despite column 4 having a larger distance to the next adjacent SSS. The shapes of the pressure with depth curves for columns 1 and 4 compare favorably with those calculated by finite element analysis (McClung et al. 1983) and show maximum pressures near mid-height and decreasing pressures away from mid-height of the snowpack. Maximum pressures for columns 2 and 3 are similar and on average slightly less than 50% of those in columns 1 and 4. Again, this is expected since end effects increase snow pressures near the free edges of a SSS. It is important to note the data presented in Fig 7 are the maximum values of pressure recorded at each PC over the entire winter season. Owing to the complex distribution of snow forces within the snowpack, and the heterogeneity of snow, it is reasonable that a given PC may experience its peak season pressure at a different time than other PCs. However, it is noted that of the 20 PCs, all but three experienced their maximum seasonal pressure in the first three weeks of February 2015 during which time the snowpack temperatures were at or above freezing. Moreover, 12 PC reached their maximum on or around 2/11/15 with a snowpack height of approximately 1.45 m.

Maximum pressures recorded for 2015-2016 and plotted along SSS height are presented in Figure 8. Interestingly, pressures at PC column 1 are the smallest with increasing pressure going from column 1 to column 4. Pressure variation with depth for columns 1 and 2 is as expected and similar to that seen during the 2014-2015 season, and maximum pressures within each column are similar. Pressure variation for PC columns 3 and 4 resemble a linear pressure increase with depth.

This is not expected, but one possible explanation is slope failure or extreme snow gliding in the 4.75 m wide unsupported tile of snowpack between SSS. Visual inspection of the ground surface adjacent to the free edge of the SSS near PC column 4 will be conducted in order gather information on possible mechanisms for the above anomaly.

Pressures at the top row of PCs were zero across the season since the maximum snowpack depth for the season of 1.5 m was below the 1.6 m height of the top crossbeam. With respect to concurrency of maximum pressures during the season, all pressure cells in the top three rows reached their seasonal maximums in middle to late February when the snowpack depth was approximately 1.3 m, while all pressure cells in the bottom two rows reached their seasonal maximums around mid-March when the snowpack depth was 1.2 m.

6. COMPARISON OF EXPERIMENTAL AND ANALYTICAL PRESSURES

Analytical expressions for slope parallel snow pressure away from SSS edges (thus free of end effects) have been developed by various researchers and provide values for average pressure to be applied uniformly over the full height of snowpack. It is not possible to provide a full description of the equations contained in the Swiss Guide (Margreth, 2007) and those by McClung (1993), and the reader is referred to those publications for complete details. Average
Fig. 5: Snow depth (top), temperature (middle), and pressure on PC4 (bottom), 2014/2015 season

Fig. 6: Snow depth (top), temperature (middle), and pressure on PC20 (bottom), 2015/2016 season
values for the experimentally measured pressures have been calculated to aid in comparison with theory. The pressure with depth profiles (Figs. 7 and 8) were integrated to determine resultant snow force and then divided by snowpack height, $H$, to obtain average pressure values.

For the 2014-2015 season, maximum pressures occurred on approximately 2/11/15 with a corresponding snowpack height of $H = 1.52$ m and density of $\rho = 390$ kg/m$^3$, yielding a value for $\rho g H = 5.83$ kPa. For the 2015-2016 season, maximum pressures for most PCs occurred within a few days of 3/20/16, with a corresponding snowpack height of $H = 1.22$ m and density of $\rho = 429$ kg/m$^3$, yielding a value for $\rho g H = 5.13$ kPa.

Predictive equations by McClung depend on snow density and the amount of glide motion, where McClung uses a stagnation depth $D$ as a measure of glide. McClung relates stagnation depth to the “glide factor”, $N$, utilized in the Swiss Guide by equation 1:

$$N = (1+3D/H)^{1/2}$$  \hspace{1cm} (1)

The glide factor depends on ground surface roughness and values are provided in the Swiss Guide as a function of surface characteristics. A value of $N = 3$ was utilized in the design of the Milepost 151 SSS and is felt to be appropriate for the site.

Values of experimental snow pressures averaged over depth and analytical average pressures are provided in Table 2. For the 2014-2015 season, pressures by McClung’s model agree very closely with those measured at the 151 Site, while the Swiss Guide value is less than the experimental by a significant margin. For 2015-2016, pressures calculated by McClung’s expressions are less than the experimental value by about 25%, while the Swiss Guide value is only half that measured experimentally.

**Tbl. 2: Average pressure (kPa)**

<table>
<thead>
<tr>
<th>Year</th>
<th>Experimental</th>
<th>McClung</th>
<th>Swiss</th>
</tr>
</thead>
<tbody>
<tr>
<td>'14-'15</td>
<td>11.9</td>
<td>11.7 - 13.5</td>
<td>11.0</td>
</tr>
<tr>
<td>'15-'16</td>
<td>14.4</td>
<td>10.3 - 11.9</td>
<td>7.4</td>
</tr>
</tbody>
</table>

7. CONCLUSIONS

Based on the results presented and discussed in this paper, the following statements about slope parallel snow pressures on rigid SSS can be made.

- Variation of pressure with depth resembles the parabolic profiles calculated by finite element analysis as described by others (Salm, 1977; McClung, 1982).

- Pressures attributed to creep appear to be much smaller than those corresponding to glide for high glide conditions. This is evidenced by extreme pressure increases during warming periods where the snowpack is not frozen to the ground surface during the day.
Extreme fluctuations in snow pressure occur daily during periods with snowpack temperatures above freezing. The mechanism is release of snowpack with subsequent glide motion late in the day, and then freezing of snowpack to ground at night. Pressures decrease because once the snow freezes to the ground surface, the snowpack in contact with the SSS deforms under creep until the stress is mostly relieved. The reduction in stress via creep deformation in a solid is a well-known phenomenon.

SSS are expected to undergo significant stress reversals or cycles during their lifetime based on the above, and consideration of fatigue in the design of structural steel SSS may be warranted.

Maximum pressures near free edges of SSS can be many times larger than those interior to the SSS width because of end effects.

Predictive expressions for average pressure by McClung appear to provide a very good estimate of average pressures throughout the snowpack height. Those contained in the Swiss Guide appear to underestimate average pressure.

Additional analyses of the collected data will be conducted, and this primarily relates to determination of average snow pressures by use of the vibrating wire strain gage data. Calculation of axial force in each of the struts and girder will allow back calculation of the total resultant snow force and its location (height).

Monitoring of the instrumented SSS will continue through the 2016-2017 winter season and thus additional comparisons of measured and analytical snow pressures will be possible. Furthermore, glide shoe instrumentation will be installed during 2016, and direct measurement of glide motion at the site will provide additional information for comparison with analytical expressions.

CONFLICT OF INTEREST
This study was not supported financially by Geokon, Inc., and none of the authors are involved financially in the production, sale, etc. of any instrumentation utilized in this research work.

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