Reliability-Based Snow Load Maps for Building Design

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ABSTRACT: This paper describes the development of a new snow load map for defining ground snow loads for building (roof) design in the state of Colorado. The newly proposed Colorado maps aim to ensure that structures designed across the state achieve the target safety index of 3 defined in ASCE 7. To achieve this target safety index, the proposed design ground snow loads may be bigger or smaller than the 50-year load that ASCE 7 currently recommends for design, depending on the site.

1. INTRODUCTION

Current practice for determining design snow loads for buildings is based on uniform hazard. In the ASCE 7-10 standard (ASCE 2010), for example, design snow loads are based on ground snow loads with a 2% annual probability of exceedance, *i.e.* having a 50-year mean recurrence interval (MRI). The roof snow load is then computed from ground snow loads based on conversion factors considering the roof's importance, thermal, and exposure factors. For buildings designed with Load Resistance Factor Design (LRFD), the pertinent load combination for determining the ultimate load (U) is:

$$U = 1.2D + 1.6S \qquad (1),$$

where D and S are the design dead and roof snow loads, respectively.

The reliability index β, also known as the safety index, is inversely related to the probability of failure for a given 50-year time-period. The commentary for ASCE 7-10 defines target reliability indices to be achieved by buildings designed according to that standard; these targets depend on the building's risk category (*i.e.,* occupancy and use) and the potential consequences of failure. For typical buildings (Risk Category II), the target 50-year safety index is 3 for member failure that is not sudden or leading to progressive damage.

In developing current code approaches, Ellingwood *et al.* (1982) showed that Equation 1 leads to designs that have β of approximately 3. This analysis considered a typical site with annual maximum ground snow loads that follow a Type II extreme value distribution and have a coefficient of variation (C.O.V.) of 0.26. A subsequent study showed that a lognormal distribution fit snow data then available in the Northeast quadrant of the United States (Ellingwood and Redfield 1983).

If the shape of the annual maximum ground snow load distribution differs from the shape assumed in the reliability calculations, β may be higher or lower than 3. In the state of Colorado, for example, the C.O.V. of annual maximum ground snow loads ranges from about 0.2 to 1.0 at different sites, due to large differences in topography and climate. For example, in the eastern plains region of the state annual maximum ground snow loads come from single storm events, which are highly variable from year to year. Ground snow load distributions at sites in this region have high C.O.V.s and relatively heavy upper tails. In the Rocky Mountains, maximum annual ground snow loads are due to snow accumulation over the winter season and have much smaller year-to-year variation.

These differences produce large variations in the reliability of roofs governed by snow loads throughout the state (Kozak and Liel 2015, SEAC 2015). When designed for the 50-year loads, the reliability achieved at mountain sites can be much higher than 3. Conversely, the reliability indices achieved at most sites in the plains are lower, due to higher variability than that considered in the original formulation of the snow load factor. This kind of variation is also expected in other western states where there are significant climatologic and geographic differences in the state and where climate varies significantly from the sites in the northeastern U.S. used to develop snow design procedures.

This study characterizes probabilistic ground snow load distributions for various sites in the state of Colorado and quantifies the necessary design snow loads to achieve a reliability of $\beta = 3$. This is accomplished by: (1) gathering and interpreting historical ground snow load data for Colorado; (2) fitting probability distributions to annual maximum ground snow data; (3) characterizing roof demand and capacity variables and assessing roof reliability; (4) determining design ground snow loads for a target of $\beta = 3.0$. This paper illustrates two Colorado locations with very different snow load patterns. We build on three previous studies of design snow loads in Colorado (SEAC 1971, Harris 1988, and SEAC 2007), but incorporate additional historical data and utilize a reliability-based approach. More details are provided in SEAC (2015).

2. GROUND SNOW LOAD DATA

2.1. Data Sources for Colorado Sites

Ground snow data for the state of Colorado is gathered from a number of sources: Snow Course, Snowpack Telemetry (SNOTEL), and National Weather Service (NWS) stations.

Snow depth and weight at Snow Course stations are measured by trained observers. An aluminum pipe is used to trap snow, such that the depth and weight of the snow in the pipe are measured. This process is typically repeated at ten locations along a half-mile course, and the average of the ten measurements is recorded (NRCS 2014). Snow Course measurements are recorded monthly and date back as far as 1936 in Colorado. A total of 177 Snow Course stations are used for this study.

SNOTEL stations are automated and tend to be installed in remote mountainous areas. They measure snow weight via a pillow that senses the pressure of the snow on top of it, electronically transmitting the data to a central repository. A total of 117 SNOTEL stations are used here.

There are two kinds of NWS weather stations: first-order and cooperative observer (CO-OP). First-order NWS stations measure snow depth and weight on a daily basis. At CO-OP stations, snow depth is measured daily, but snow weight is not. Therefore, ground snow weights at these stations must be estimated from snow depth. Data is gathered from a total of 303 NWS CO-OP stations and six first order stations.

2.2. Assembly of Colorado Snow Data

Data from the 603 NWS, SNOTEL and Snow Course stations is assembled into 327 “snow sites” in the state. There are fewer snow sites than snow recording stations because: (1) where SNOTEL stations have replaced Snow Course stations, they are treated as a single site; (2) sites with less than 30 years of snow data are omitted because their snow records are considered too short to be used for the statistical analyses performed in this study; (3) stations in very close proximity (*i.e.* close enough so that no difference is expected in their ground snow loads) are combined into single sites. [1] Station combination is based on proximity and similarity of the terrain and topography. Mountain stations are combined into a single site when they are within two miles and 300 ft. elevation of each other, and plains stations are combined if they are within 10-15 miles and 500 ft. elevation of each other. The proximity that is necessary for multiple stations to be considered as one site is based on expert judgment considering the relative spatial variability of ground snow loads in different regions in Colorado.

Each snow site contains the following information: history of annual maximum snow weights and/or depths, latitude, longitude, elevation, and names of contributing snow stations. For cases where a snow site is a combination of two or more snow stations, the annual maximum weights are taken as the maximum values from all of the contributing stations for each year.

2.3. Depth to Weight Conversions

Annual maximum snow weight is estimated from annual maximum snow depth where snow weight data is unavailable. Following Tobiasson and Greatorex (1997), the relationship between snow depth and snow weight is assumed to follow a power curve.

In order to determine a relationship between snow depth and snow weight, the snow sites in this study are classified as either "settled" or "compacted" (SEAC 2007). Settled snow sites, typically found in the plains, are sites at which most of the snowpack tends to melt between snowstorms. Compacted snow sites, typically found in the mountains, accumulate snow throughout the winter. Snowpack at these sites tends to be denser than at settled snow sites, due to consolidation over the season.

Examination of snow sites for which both weight and depth measurements are available shows that the relationship developed by Tobiasson and Greatorex (1996) is unbiased for predicting snow weights at settled snow sites in Colorado, where:

$$W = 0.28 * D^{1.36} \tag{2}$$

Here, W is annual maximum snow weight in psf and D is annual maximum snow depth in inches. For compacted sites, a separate relationship based on Colorado Snow Course data is developed, as shown in Figure 1.

$$W = 0.58 * D^{1.26} \tag{3}$$

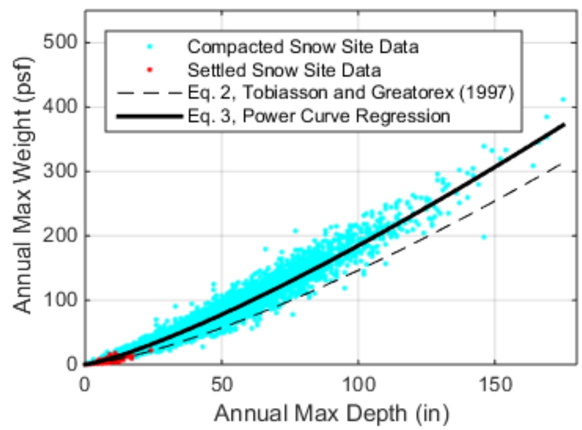

Figure 1: Relationship between annual maximum weight and annual maximum depth in Colorado.

3. PROBABILITY DISTRIBUTIONS FOR ANNUAL MAXIMUM GROUND SNOW LOAD

Probability models are fit to the observed annual maximum ground snow load data in two stages. In the first stage, probability models are fit individually to each snow site's data. In the second stage, the shape of the distribution tail at each site is modified to reflect typical tail shapes for other sites with similar climatic and geological features.

3.1 Probability Models Fit to Individual Snow Site Data

Figure 2a provides an example histogram of annual maximum snow load for a typical plains snow site, Denver-Stapleton. As in this example, the histograms for most sites on the plains are strongly skewed, and the upper tail of the distribution becomes particularly important for

[1] In addition, some NWS records are actually combinations of nearby sites due to movements of the recording location over time, meaning that a number of station combinations

reliability analysis, because structural failures tend to occur when snow loads are much bigger than the design value (*i.e.* loads having long MRIs). As a result, we fit each candidate distribution to the upper one third of the data (hereafter referred to as "tail-fitting"). For the purpose of the tail-fitting, we consider four two-parameter probability models: Normal, Gamma, Lognormal, and Log-Gamma. Of these distributions, the Normal has the lowest probability density in the upper tail and the Log-Gamma has the highest density in the upper tail. Although a number of other distributions have been used to model ground snow loads, these four are considered to be sufficient to represent the historical data at all sites, because of the tail-fitting methods.

To fit the distributions to the data, for distributions belonging to the Normal family, the data points (*i.e.* annual maximum snow weights recorded at the snow site) are rank-ordered and plotted on probability paper. As illustrated in Figures 2b-c, a least-squares linear regression line is fit to the upper third of the data to determine the distribution parameters. Distributions are also fit to the entire data sets, but for illustration purposes only.

The tail-fitting approach for Gamma family distributions is similar. However, since Gamma distribution parameters (shape and location) are coupled, there is no standard probability paper for plotting the data. Instead, the observed data values are plotted against values that are computed from a trial Gamma distribution. The parameters of the trial Gamma distribution are refined until a least-squares linear regression of the theoretical values with the observed values results in one-to-one line.

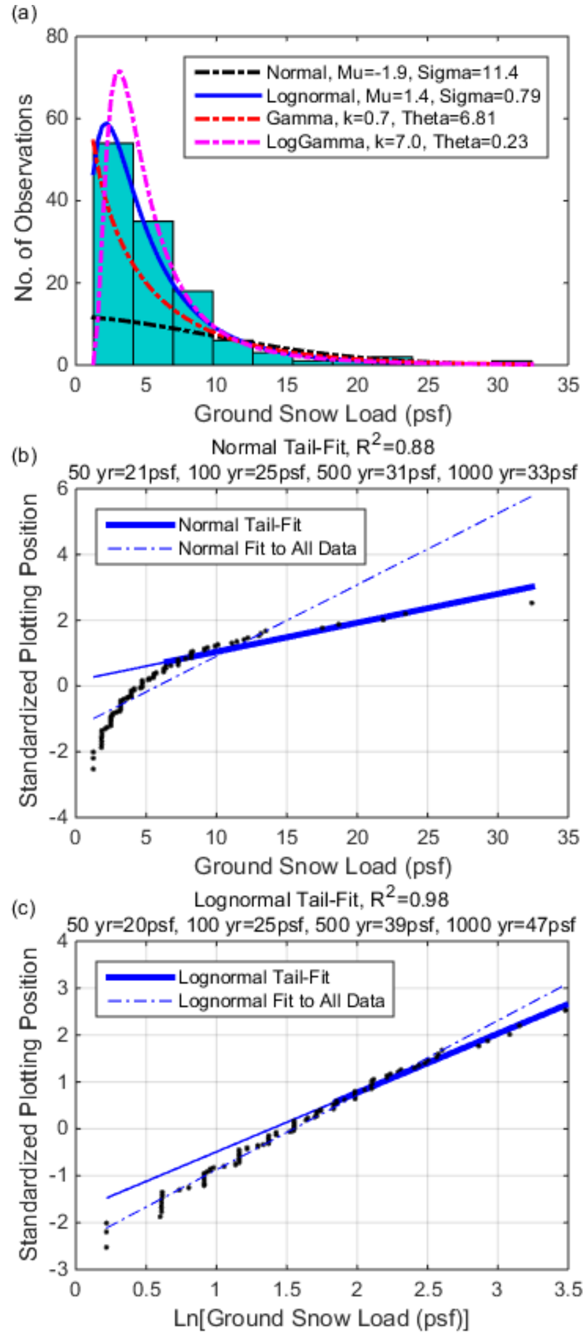

Figure 2: (a) Histogram of Denver-Stapleton historical snow site data with tail-fitted probability density functions overlaid. (b)-(c) Normal and Lognormal distributions fit to all of the data and to the tails only. The thick parts of the solid lines identify the upper third of the data used for tail-fitting. The labels above each plot indicate the distribution type, R^2 goodness of fit for the tail-fit least squares regression, and ground snow loads with MRIs of 50, 100, 500, and 1000 years from the tail-fit distribution.

Strengths and weaknesses of the site-specific tail-fitting approach are highlighted by Figure 2. They work well for predicting moderately rare loads (*e.g.* MRI of 50 years) but not extremely rare loads (*e.g.* MRI of 1000 years). Notice that the 50-year loads, *i.e.* loads with a MRI of 50 years, are well-predicted by both distributions shown; in fact, all four tail-fit distributions produce a 50-year load between 20 and 22 psf at Denver-Stapleton. In contrast, distributions fit to the entire data set predict 50-year loads of 15, 17, 16, and 26 psf, for Normal, Lognormal, Gamma, and Log-Gamma, respectively. For comparison, the top three recorded values in the 121-year record are 22, 23, and 32 psf. There is also significant variability in the more extreme values, *e.g.* the 500 and 1000-year loads, even among the tail-fit distributions. The discrepancies in extremely rare loads (500 and 1000 year loads) that are predicted by the different distributions are the result of having too few years of data (50-100 years of data). These extrapolations depend heavily on the distribution that is selected.

3.2 Clustering of Snow Sites to Modify Distribution Tail Shapes

Since the snow sites have between 30 and 120 years of data, the shapes of the tails of the probability distributions beyond the 100-year values are difficult to estimate. DePaolo (2013) showed that clustering of sites could be used to improve understanding of ground snow loads at snow sites by considering what we know about similar sites. Here, the tail of each site-specific distribution is modified to reflect a more general tail shape determined from a cluster of sites with similar climatic and geographic features, thus improving our estimates of the distribution shapes in the extreme upper tails. Snow sites are clustered into groups of 20 sites or greater, based on similarities in altitude and climatic region.

The tail shape for a cluster of sites is modeled by combining the data for all of the snow sites in the cluster into one data set. By combining data from the entire cluster, we obtain data records on the order of 1000 years rather than 50-100 years[2], increasing our confidence in the behavior of the far tail (*e.g.* snow loads with MRIs as great as 1000 years). Since the magnitude of ground snow loads at different sites is expected to vary, data from each site are first scaled so that the scaled site 20-year MRI ground snow load matches the average 20-year MRI for all the sites the cluster. The cluster distribution is then tail-fit for the top 10% of the combined data set.[3] Once the shape of the tail for the cluster is determined, the tail shape is rescaled back to the 20-year MRI load of the individual site of interest, such that the snow distribution for each snow site retains the 20-year MRI from its historical record, but the tail shape benefits from the longer record obtained through clustering. SEAC (2015) describes the clustering approach for modifying the extreme upper tails in detail.

4 RELIABILITY ASSESSMENTS

4.1 Monte Carlo Reliability Assessment

Reliability assessments are used to determine the reliability index for roofs designed according to the 50-year load, and, alternatively, what design load value would be required to achieve a reliability index of 3.0. The reliability analysis considers simply supported steel roof beams that are governed by snow loads.

Reliability at each site is assessed with Monte Carlo Simulation methods (Fishman 2006). For each assessment, ten million Monte Carlo simulations are performed, each representing a single year. Each simulation computes a random demand (*i.e.* roof dead and snow load) and random load-carrying capacity. If the moment demand is greater than the moment capacity in a given simulation, a failure is

[2] This analysis assumes that snow records at each site are independent. By combining nearby stations into single snow sites before reaching this step, we decrease the probability of double-counting extreme values from the same snowstorms, but we do not eliminate it.

[3] Tail-fits for combined data are performed for the top 10%, rather than the top one third of the data, because they are intended to estimate the far tail, and the larger cluster data sets have significant numbers of data points (>50) above that threshold.

assumed to have occurred. The total number of failures divided by the number of simulations is the approximate annual probability of failure, which is converted to the probability of failure in 50 years using the Poisson distribution. The probability of failure is then converted to a 50-year reliability index. The Monte Carlo Simulation is repeated for a range of design ground snow loads, to produce a curve relating design ground snow load to the reliability index under varying design conditions.

To conduct the reliability assessment, we first design a roof for the design ground snow load of interest. The roof consists of wide flange steel beams that are 30 feet in length and have a tributary width of 30 feet, considering a dead load of 15 psf.[4] The roof snow load is taken as 0.7 times the ground snow load based on the ASCE 7 Standard (ASCE 2010) for typical thermal and exposure characteristics (coefficients of 1.0 in ASCE 7). The required section modulus for a simply supported wide flange steel roof is computed for the factored dead and ultimate snow loads, and a strength reduction factor of 0.9. Deflection limits are not considered in the design process.

4.2 Uncertain Capacity Variables

In the reliability analysis, the true moment capacity of the steel roof member is computed considering uncertainty in the yield strength and plastic section modulus of the section. The steel yield strength is taken to be lognormal distributed with a mean value of 1.1 times the nominal yield strength of 50 ksi, with a logarithmic standard deviation of 0.09. The plastic section modulus is normally distributed with a mean value of 1.05 times the required section modulus. The 1.05 factor accounts for the increase in section size that would be achieved if a discrete steel section was selected in the design. The plastic section modulus has a coefficient of variation of 0.05 (Galambos and Ravindra, 1978; Lind, 1977).

4.3 Uncertain Demand Variables

Demand variables that are considered in the reliability assessment are roof dead load and roof snow load. Following Ellingwood *et al.* (1982), the roof dead load is assumed to be normally distributed with an expected value of 1.05 times the design dead load and with a C.O.V. of 0.1.

The roof snow load in Monte Carlo analysis is modeled as a function of two random variables: the ground snow load, which is discussed in Section 4, and the ratio of roof snow load to the ground snow load, *i.e.* the ground-to-roof conversion factor. Ellingwood and O'Rourke (1985) estimated that the ground-to-roof conversion factor for snow loads is lognormally distributed with a median of 0.47 and logarithmic standard deviation of 0.42, based on data for roofs with varying exposure and thermal conditions collected by O'Rourke *et al.* (1982). More recent data collected by Høibø (1988, 1989) (supplied by Thiis and O'Rourke, 2015) shows that a significant portion of the variation of the ground-to-roof conversion factor can be explained by the magnitude of the ground snow load. Figure 3 shows that the ratio of roof snow load to ground snow load decreases as ground snow load increases, because larger ground snow loads tend to be due to season long accumulation, which allows time for wind, thermal and sublimation processes to remove more snow from the roof.

Like Ellingwood and O'Rourke (1985), we assume the ground-to-roof conversion to be lognormal. However, we condition the conversion factor on the ground snow load level, such that the median and logarithmic standard deviation of the distribution are a function of the ground snow load. Figure 3 shows the Thiis and O'Rourke (2015) data with the results of our statistical analysis, using local polynomial re-gression, overlaid. The thick black line is the analytical function that is used in this study to estimate the median ground-to-roof conversion as a function of ground snow load, obtained by fitting an exponential function to the moving

[4] A series of sensitivity studies conducted by the authors shows that the reliability results are not sensitive to the roof geometry and other design assumptions.

median. The modeled ground-to-roof conversion factor has an asymptote that is fixed at 0.4, which is nearly reached within the range of available data. There are insufficient data for ground snow loads greater than 100 psf to determine whether a median ground-to-roof conversion factor less than 0.4 is acceptable for such conditions.

The logarithmic standard deviation of the ground-to-roof conversion factor is 0.33 for ground snow loads greater than 33 psf and varies linearly from 0.1 to 0.33 for ground snow loads between 0 psf to 33 psf. For simulation purposes, an upper bound ground-to-roof conversion factor of 1.25 is enforced. Of all the demand and capacity variables considered in the reliability analysis, the ground-to-roof conversion factor and the ground snow load distribution are the most uncertain.

4.4 Reliability Assessments for Selected Colorado Sites

Reliability assessments are presented for Denver and Keystone Mine, because these locations exhibit typical plains and mountain climatology in the state of Colorado. The distribution of annual maximum snow loads in Denver is positively skewed (Figure 2), with a mean annual maximum snow load of 6 psf and a large C.O.V. (approximately 0.80). The distribution of annual maximum snow loads at Keystone Mine has a mean value of 105 psf, a low C.O.V. (approximately 0.35), and an unskewed distribution.

Figures 5 and 6 show the results of the reliability assessments for Denver and Keystone Mine, with and without the minimum snow load for low-slope roofs included in the design procedure.[5] The green dashed lines represent the 50-year MRI ground snow load at each site (*i.e.* the design ground snow load per current methods, but with an improved estimate of the 50-year value obtained from the tail-fitting procedure described in this paper). The red dashed lines represent the required design ground snow load to achieve a reliability index of 3.0 (*i.e.* the "risk-targeted" design snow load), assuming that the LRFD load combination from Equation 1 is used for design.

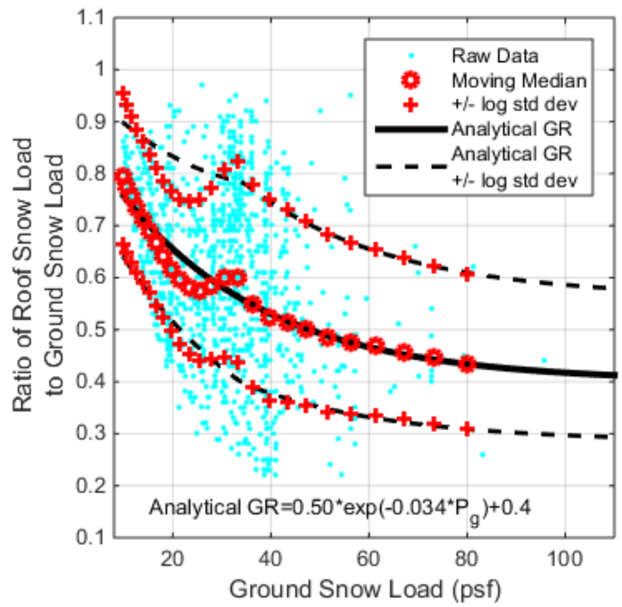

Figure 3: Ratio of roof snow load to ground snow load (GR) vs. ground snow load (P_g) with the analytical ground-to-roof conversion overlaid. Data was collected by Høibø (1988, 1989) and provided by Thiis and O'Rourke (2015).

Looking first at the 50-year MRI loads for Denver and Keystone Mine, it is apparent that designing the 50-year MRI loads does not produce consistent reliability between sites (2.0 for Denver and 3.5 for Keystone Mine). ASCE 7 reliability targets are not met in the plains, but are exceeded in the mountains.

In order to produce a reliability index of 3, the design ground snow load in Denver should be approximately 35 psf, 1.75 times higher than the 50-year MRI ground snow load of 20 psf. Alternatively, if the 50-year MRI load were taken as the design load in Denver, then the LRFD load factor for snow loading would need to be 2.8 instead of 1.6 to produce a reliability index of 3.0. We observe, however, that the increase in design ground snow loads from 20 to 35 psf in Denver is consistent with current local

[5] For low-slope roofs only, ASCE 7 defines minimum roof snow loads equal to 20 psf or the ground snow load, whichever is lesser, times the snow importance factor.

practice. The city of Denver already requires a minimum flat-roof load of 25 psf for Risk Category II buildings (City of Denver 2011). A design ground snow load of 35 psf corresponds to a flat-roof snow load of 24.5 psf.

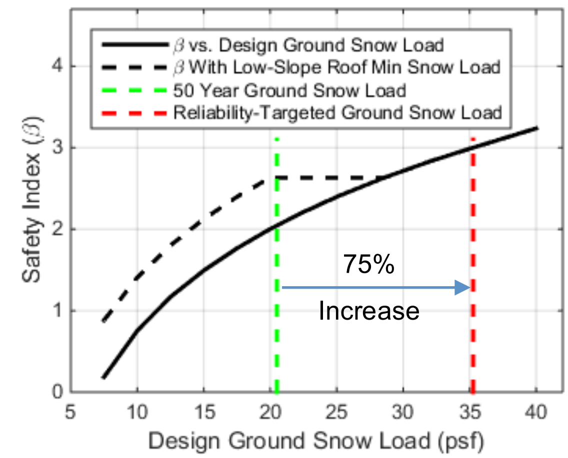

Figure 4: Reliability index vs. design ground snow load for Denver.

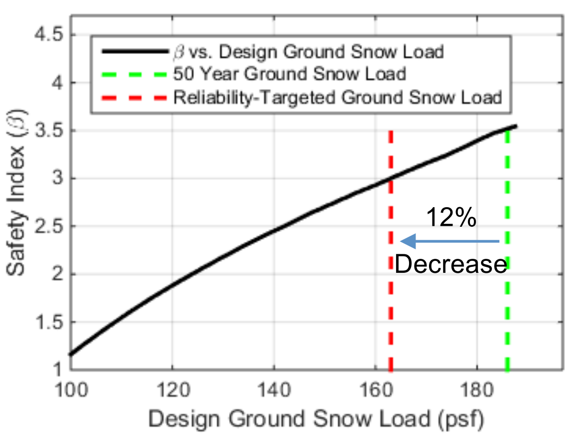

Figure 5: Reliability index vs. design ground snow load for Keystone Mine.

For Keystone Mine, a design ground snow load of 163 psf is sufficient to produce a reliability index of 3, which is 12% lower than the 50-year MRI ground snow load of 186 psf. If the 50-year MRI load were taken as the design load in Keystone Mine, then the LRFD load factor for snow loading would need to be 1.4 instead of 1.6 to achieve the target reliability.

5. CONCLUSIONS: A MOVE TOWARD UNIFORM RELIABILITY DESIGN SNOW LOAD MAPS

This study demonstrates that the current LRFD snow load factor of 1.6, when coupled with a design snow load with a 50-year mean recurrence interval, does not produce consistent reliability for sites across Colorado. The risk of snow-induced roof failure is higher in the plains than in the mountains. This finding suggests that current approaches do not provide adequate and consistent safety against structural failure. Although the study focuses on Colorado, the same discrepancies would be observed in any region with significant variability in climate.

This study proposes new approaches for determining snow load maps that provide consistent reliability against ultimate limit states. It would be impractical and unnecessarily complicated to impose LRFD snow load factors that vary with location. Therefore, a reliability-targeted ground snow load map is proposed for the state of Colorado that is similar in concept to the risk-targeted maximum considered earthquake ground motion maps adopted in ASCE 7-10 (Luco *et al.* 2007, ASCE 2010). Such a map would be composed of design ground snow load values that achieve a target risk of snow-induced structural failure when factored by 1.6. This target corresponds to a β of 3, or approximately 0.13% probability of failure in 50 years for ordinary buildings.

The reliability analysis suggests that design ground snow load values in the plains of Colorado should be on the order of 1.75 times the 50-year MRI loads to achieve the target risk. This finding is consistent with local standard practice: engineers already use snow loads that are higher than the 50-year MRI load for designing buildings in Denver and other populated communities on the eastern side of the Rocky Mountains. Design snow loads in the mountains will be on the order of 10% less than the 50-year MRI loads. This reduction occurs because season-long accumulation in heavy snow areas reduces variability in the ground snow loads. These conclusions are supported here by two case study examples of Keystone Mine and Denver, but a substantial number of other sites have also been examined.

Production of a reliability-targeted ground snow load map for the state of Colorado is underway. The proposed approach could be used to develop reliability-targeted ground snow load maps for any region for which snow loading is a significant design consideration and where significant climatic variation exists.

5 ACKNOWLEDGMENTS

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