HOW RELIABLE ARE DESIGN AVALANCHE LOADS? A SYSTEMATIC APPROACH TO ESTIMATE THEIR UNCERTAINTY.

Mark Schaer[1*], Katharina Fischer[2], Stefan Margreth[1]

[1] *WSL Institute for Snow and Avalanche Research SLF, 7260 Davos Dorf, Switzerland*
[2] *Matrisk GmbH, 8910 Affoltern am Albis, Switzerland*

ABSTRACT: The assessment of avalanche loads depends partly on well-founded facts such as observed avalanches, but the avalanche expert generally also has to make many assumptions that are difficult to base on objective evidence. This is particularly true for avalanche tracks with complex release zones and for the assessment of avalanches with a long return period, where little empirical data is available. However, an engineer requires precise load values for example for the design of a snow shed. We present a study where we analysed a well documented avalanche track in Davos that has a snow shed at the bottom. To estimate the uncertainty of the avalanche loads on the snow shed, we varied the decisive input parameters to perform numerical avalanche simulations systematically and asked three experts to estimate the probability of each parameter value. Several thousand avalanche-dynamic simulations with the software RAMMS were performed to cover all possible parameter combinations and the avalanche load on the snow shed was computed for each run. Using the probabilities that were estimated for the input parameters, we calculated the probability distribution for the avalanche load and the probability for the load exceeding the bearing capacity of the structural system of the snow shed. The main conclusions are: (a) Although the involved experts have all a long experience and a similar professional background, their estimations varied by a factor of 2.8 for the maximum load related to a 300-year return period. (b) For the snow shed, we got a failure probability in the order of 1E-3 per winter. This number is compatible with the low number of documented snow shed collapses, but below the requirements of European building codes which require an annual failure probability of 1E-5 or lower, depending on the consequence class.

Keywords: avalanche loads, avalanche dynamic simulations, snow shed, probabilistic approach, failure probability, building codes

1. INTRODUCTION

For the design of structures exposed to avalanches, Swiss guidelines (i. e. Margreth et al. (2015), ASTRA (2007)) specify that avalanches with two return periods (in most cases 30 years and 300 years) have to be considered for the design. These return periods essentially define a variable and an accidental avalanche action for the proofs required by building codes (e. g. SIA 260 (2013), EN 1990 (2001)).

The guidelines describe the load cases which have to be considered for design, but they do not specify how the avalanche expert has to define an avalanche scenario which is the base to perform avalanche simulations. The manual 'Berechnung von Fliesslawinen' (calculation of dense flow avalanches) (Salm et al., 1990) contains for example instructions how the fracture depth for a given return period may be defined. Apart from adaptions due to the use of new numerical models, since 1990 little has changed regarding the procedures to define avalanche scenarios. The most problematic point of avalanche simulatiions is the fact that the expert has to choose many input parameters such as release area subjectively because the definition of reproducible rules is impractical. Apart from that uncertainty, at many sites the controlling avalanche input parameters might deviate far from defined standards.

Any expert will be very well aware of the uncertainty and arbitrariness of his simulations. As it is not practicable to perform simulations which cover the whole range of possible input parameters, the expert will concentrate on a single 'most probable' scenario for the analysed return period.

In our analysis we try to quantify the range of uncertainty of avalanche load assessments by varying the relevant input parameters systematically.

2. EXPERIMENTAL SITE, METHODS AND DATA

The 'Salezer' avalanche track in Davos consists of a catchment area of some $600'000\,\mathrm{m}^2$ and extends from 1558 to $2536\,\mathrm{m}$ above sea level (see Figure 1). Between $1700\,\mathrm{m}$ and the top of the catchment area, around $60\,\%$ of the area is steeper than 30° and

*Corresponding author address:
Mark Schaer, WSL Institute for Snow and Avalanche Research SLF, Flüelastrasse 11, CH-7260 Davos Dorf
email: schaer@slf.ch

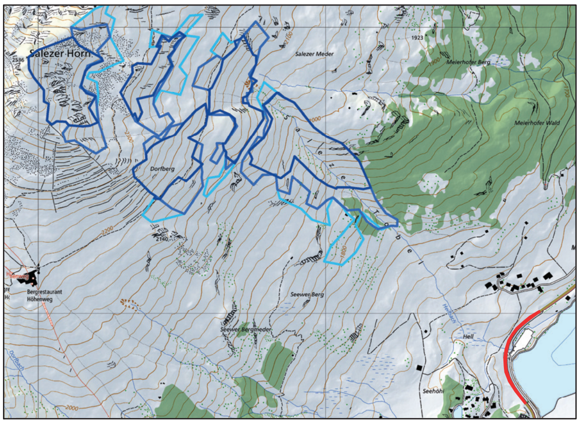

Figure 1: Map of the Salezer avalanche track, with the snow shed protecting the road (red line). We have identified five potential avalanche release zones (blue polygons) and assume that avalanches can start from a small (dark blue), mid-size (blue) or large (light blue) part of these release zones.

therefore potential release area. The topography is rather uneven. Areas with a slope clearly steeper than 30° alternate with areas flatter than 20° and areas where the slope changes on a small scale between steep and flat spots. Therefore the delimitation of avalanche release areas is not straightforward.

Most of the avalanches that release in this catchment area will be canalised in the V-shaped Salezer gully. At $1700\,\mathrm{m}$, the gully ends on an alluvial fan with an inclination of 15°. The main access road to Davos crosses this alluvial fan protected by a 400 m long snow shed. We have used the calculated velocity, flow height and deposition height at the location of the snow shed to quantify the uncertainty of avalanche load assessments.

For the choice of the main input parameters we have asked three avalanche experts (see Figure 2). These experts have worked for several decades as consultants at the SLF and they perform avalanche hazard assessments on a regular basis and may be considered to be very experienced.

The avalanche dynamic simulations were performed with RAMMS (Christen et al., 2010). We used the RAMMS version 1.6 which allows to perform batch calculations and to account for secondary avalanche releases.

The calculation grid was based on the terrain model swissALTI3D using a grid size of 5 m. The input for the batch RAMMS calculations was prepared with a bash-shell script. For the post-processing and the statistical analysis we applied ArcGIS, Python and bash-shell scripts.

Simulations for return periods T of $t1 = 10$, $t2 = 30$ and $t3 = 300$ years were performed. The annual exceedance probability for avalanches of the respective periods is e_{t1}, e_{t2} and e_{t3}.

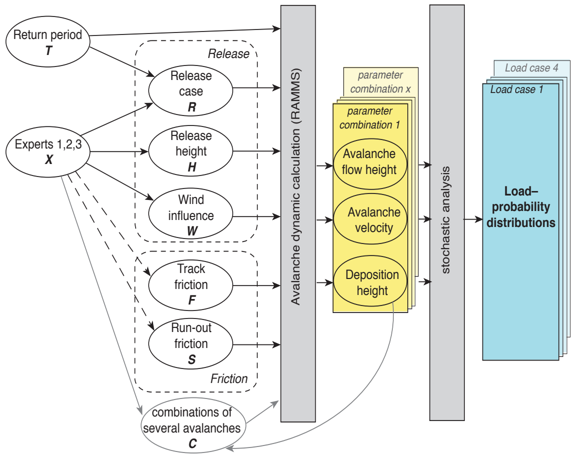

Figure 2: Workflow for the avalanche dynamic simulations and stochastic analysis. We calculated load-probability distributions for four load cases defined in ASTRA (2007): (1) avalanche flow over bare ground, (2) avalanche flow over a winter snow cover, (3) avalanche flow over old avalanche depositions and (4) static load of the avalanche depositions. The combination of several avalanches (input parameter C) is only used for load cases 3 and 4.

We varied the five most relevant input parameters (see Figure 2 and the list below) in order to cover the parameter range an expert might chose. Lacking more information, we assumed mutual independence of these parameters.

Release case R Choosing the location and size of the release area is probably the most important decision in an avalanche simulation. Each expert defined four release area cases: a rather optimistic ($r1$), a realistic ($r2$), a rather pessimistic ($r3$) and a very cautions ($r4$) case. For each release case and return period the experts defined in which release areas they expect primary or for secondary avalanche release.

Further each expert estimated for each case the probability of an release area being larger than he had assumed (the exceedance probability e_{r1} to e_{r4}, see Table 1).

Release height H We made simulations for two cases: $h1$ is the release height according to the Swiss guidelines, $h2$ is a slightly more conservative value. For $h2$ the release depth is on average $10\,\%$ larger than for $h1$. *Note: For both cases, $h1$ and $h2$, the chosen release height varies depending on on return period, altitude and slope angle of the release zone.*

Each expert estimated the exceedance probabilities e_{h1} and e_{h2} of H.

Wind influence W In exposed terrain, snow drift accumulations may increase the avalanche release volume. Simulations were performed

Table 1: Estimated probability distribution of the input parameters.

	annual exceedance probability			
Return period T	e_{t1}	e_{t2}	e_{t3}	
per definition	0.1	0.033	0.003	
	absolute exceedance probability			
Release case R	e_{r1}	e_{r2}	e_{r3}	e_{r4}
expert 1	0.65	0.5	0.25	0.1
expert 2	0.7	0.5	02	0.1
expert 3	0.4	0.3	02	0.1
Release height H	e_{h1}	e_{h2}		
expert 1	0.6	0.5		
expert 2	0.5	0.4		
expert 3	0.3	0.1		
Wind influence W	e_{w1}	e_{w2}		
expert 1	0.7	0.4		
expert 2	0.7	0.3		
expert 3	0.8	0.2		
	probability per class			
Track friction F	p_{f1}	p_{f2}	p_{f3}	p_{f4}
for all experts	0.16	0.28	0.28	0.28
Run-out friction S	p_{s1}	p_{s2}	p_{s3}	
for all experts	0.34	0.33	0.033	
	annual exceedance probability			
Combinations C	e_{c1}	...	...	e_{c15}
expert 1	0.05	...	...	0.0020
expert 2	0.05	...	...	0.0022
expert 3	0.07	...	...	0.0028

without wind influence ($w1$) and with wind influence ($w2$). The average avalanche volume increase due to wind was $30\,\%$.
Also for W, exceedance probabilities e_{w1} and e_{w2} were estimated by each expert.

Track friction F Avalanche friction parameters depend on track shape and avalanche volume, but snow type also affects the friction parameters. We model the variability of the friction F by four values, $f1$ to $f4$ and estimate their probability distribution p_{f1} to p_{f4}.

Run-out friction S Wet or humid snow conditions in the run-out can contribute to a sudden stop and high avalanche deposits on the snow shed. The range of these wet snow conditions in the run-out is modelled by the parameter values $s1$, $s2$ and $s3$ and their distribution with p_{s1} to p_{s3}.

Combination of several avalanches C For load case 3 and 4 of ASTRA (2007) the case of several large avalanche within one winter has to be accounted for. To estimate the probability distribution of such multi-avalanche events, we have defined a set of fifteen possible combinations. *To illustrate this: one combination is 'three avalanches with a return period of 10 years in the same winter and another combination is 'two avalanches with return periods of 30 and 10 years in one winter'.* Each expert then estimated the

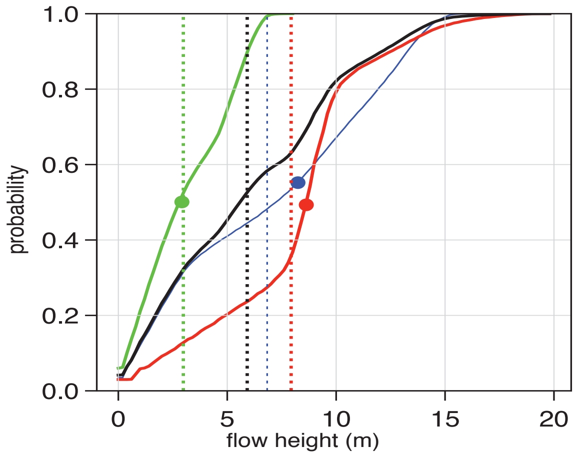

Figure 3: Avalanche flow height in a central part of the Salezer snow shed for a 300 year return period. The distribution of the flow height according to expert 1, 2 and 3 is drawn in blue, red and green respectively. The average of the three distributions is in black. The horizontal axis is the flow height in meters and the vertical axis is the probability that an avalanche does not exceed this flow height. The dots show the best estimate for each expert and the dotted line is the average flow height.

return period (or exceedance probability e_C) for each of these combinations.

After defining all input parameters, we performed RAMMS-simulations for all possible parameter combinations to get the flow velocity, flow height and deposition height at the location of the snow shed for each run. The loads of the different load cases were based on these values.

3. STOCHASTIC ANALYSIS

Analysis of load case 1 and 2 of ASTRA (2007): For each simulation output (flow height, velocity, deposition height) a multivariate interpolation for all R, H, W values was made accounting for the exceedance probabilities e_R, e_H and e_W to derive a load distribution for each of 12 possible combinations of F and S values. Then these 12 distributions were weighed with their respective probabilities (p_F, p_S) to get the distribution for each expert and return period. (coloured lines in Figure 3). The load distributions for the 30 and 300 year return periods were then used to calculate the overall probability distribution of the flow height (i. e. maximum values for each return period as shown in Figure 5).

Analysis of load case 3 and 4: The analysis procedure was essentially same as in load case 1 and 2. The main difference was that load distributions were calculated for e_C (for the return periods estimated by the experts for each avalanche combination), rather than for e_T (for fixed return periods of 10, 30 and 300 years). Figure 4 shows the calculated load distribution for expert 1 and case 4.

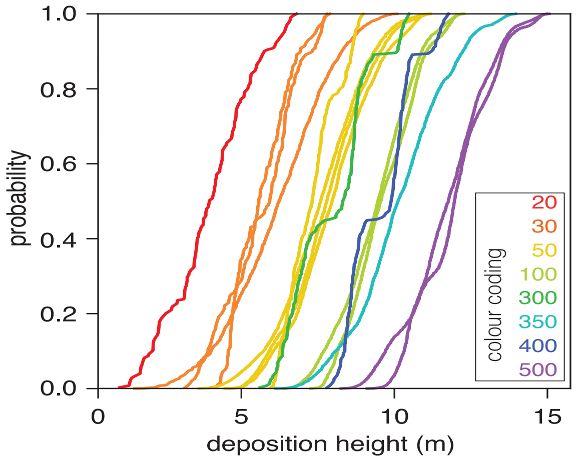

Figure 4: Deposition height on the shed by multiple avalanches (load case 4). The height distribution for fifteen combinations is shown for expert 1. The horizontal axis is the total deposition height in meters and the vertical axis is defined as in Figure 3. The line colours indicate the estimated return period (years) for each combination. Note that an increasing return period does not always result in increasing heights.

4. ESTIMATION OF THE FAILURE PROBABILITY

It is important to see that the goal of our study was not to get the failure probability for a particular snow shed. Such a value would have little meaning for other locations. Therefore we concentrate on showing the general dependence of the failure probability on the width of the avalanche load distribution and on estimation errors for the design load. *Note: since we did not analyse the the effective bearing capacity of the Salezer snow shed or the design loads used for building it, the failure probability is a theoretical and not a true value for this particular snow shed.*

As the conditions which define the size of an avalanche (or the input parameters when we are talking about numerical simulations) are random variables, a design avalanche too has to be treated as having a probability distribution. However, avalanche experts will normally not calculate the probability distribution for the avalanche loads. Instead they will just provide a single 'representative' load.

It is straightforward to see that, for the same representative load, a wider load distribution (that means more events which will be larger than the 'representative' load) will result in a higher failure probability.

Of course it is also true, that a snow shed design has a higher failure probability when it has been designed according the loads defined by an optimistic expert (who will under-estimate the representative loads) than for a pessimistic expert.

We will now quantify this failure probability using a probabilistic model (see JCSS (2001)). This model compares basically the avalanche load distribution (span) is compared with estimated safety margins coming from the difference between reality and the the action, geometrical, mechanical and failure mechanism models used for design.

As a model assumption, we postulate that the average load distribution for all experts represents the 'true' avalanche load (the black line in Figure 3) and that the shed has been designed with a safety factor of 1.0 for the 300 year value of this 'true' load (the load indicated by the black dot in Figure 5). *As to make clear this 'truth' is a model assumption and not the reality, we will always write 'true' in apostrophes.* Using the overall probability for the load distribution (the black line in Figure 5, because of our model assumption this value is also 'true') we could then estimate the failure probability. The black circles in Figure 6 show this probability for the failure mechanism of concrete steel.

The blue, red and green crosses show the failure probability for a shed that has been designed according to the loads given by experts 1, 2 or 3 respectively (assuming same representative load as before as 'true').

5. DISCUSSION AND CONCLUSIONS

(1) A comparison of the results of the experts shows that the chosen input parameters may vary very much and consequently, the calculated avalanche loads also vary much. For a 300 year return period and the centre of the snow shed, , we got a factor of 2.8 for the representative load.

(2) For new snow sheds, we found no critical issues in the design procedure according to ASTRA (2007). Although we found that the design for variable loads (using a load coefficient of 1.5) is not decisive, this case is in general covered by the design for accidental avalanche loads (therefore we didn't show the variable load case here).
We also rate a typical failure probability of 1E-3 as barely satisfactory for the case of snow sheds, where the load variability and uncertainty is big, the costs of the bearing structure are high and the consequence of a failure is rather low.
From comparison with the empirical failure probability (very few snow sheds have collapsed so far under avalanche load) we also assume our estimations are rather pessimistic. In reality, there must be 'hidden safety' not present in our models.

(3) More problematic is a failure probability of 1E-3 if an existing snow shed is being examined according to SIA 269 (2011). In our case, the failure probability we found is clearly above acceptable values (1E-5 or lower, depending on the consequence class).

(4) Records of past avalanche activity allow a plausibility check of input parameters and calculated

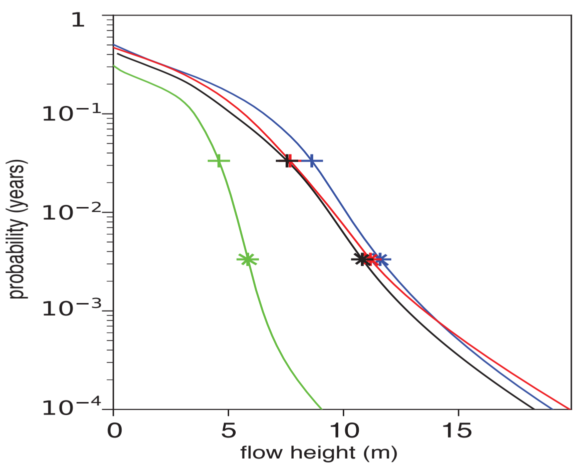

Figure 5: Overall probability distribution of the flow height (load case 1 in ASTRA (2007)). The horizontal axis flow height in m.The vertical axis is the annual probability that the load will be exceeded. As in Figure 3 the colours indicate the different experts. The values for the 30-year and the 300-year return periods are marked with a cross respectively a star.

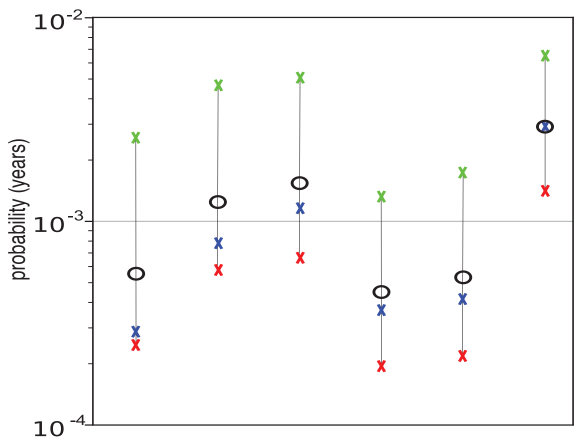

Figure 6: Failure probability of the concrete steel for loading case 1 (avalanche on bare ground). The vertical axis shows the annual failure probability. Each of the vertical black lines indicates a different section along the shed. The black circles show the failure probability for design according to the 'true' load and the blue, red and green crosses show the failure probability for a snow shed that has been designed according experts 1, 2 or 3 respectively. For most sections of the snow shed, the failure probability is of order 1E-3 and it varies by an order of magnitude from expert to expert.

avalanche loads and result in a better estimate of the representative load. However, in most situations, the quality of the documented avalanches is insufficient for an in depth analysis. Although the Salezer avalanche track is well suited for analysis since it lies so close to the SLF and it has been thoroughly monitored and analysed for decades, little analysable data of observed actual release areas, release heights or deposition depths is available.

6. OUTLOOK

Our analysis does not allow to give a recommendation, how to proceed when the proof of safety according to SIA 260 (2013) fails for an existing snow shed.

In Switzerland, a planner is required to evaluate the benefit-cost ratio of structural avalanche mitigation measures as regulated in BAFU (2015) and Wilhelm (1999). Only measures which full-fill the economic criteria of these regulations can be built (see Bründl et al. (2009)). In our opinion, benefit-cost analysis could be performed as well for the rating of maintenance cost of existing measures.

Currently we're still engaged in more case studies on order to be able to elaborate recommendations for such a case.

ACKNOWLEDGEMENTS

The authors would like to thank the research section of the Swiss federal Road Office FEDRO for a research grant which facilitated our study and for practical advice.
Further we thank the avalanche dynamics team and programmers at the WSL for their support in adapting the RAMMS simulation program for our needs.

REFERENCES

ASTRA (2007). *Richtlinie Einwirkungen auf Lawinenschutzgalerien.* Bundesamt für Strassen ASTRA + SBB AG Infrastuktur.

BAFU (2015). *EconoMe 4.0 Wirksamkeit und Wirtschaftlichkeit von Schutzmassnahmen gegen Naturgefahren.* Bundesamt für Umwelt (BAFU), Bern.

Bründl, M., Romang, H. E., Bischof, N., and Rheinberger, C. M. (2009). The risk concept and its application in natural hazard risk management in switzerland. *Natural Hazards and Earth System Sciences*, 9(3):801–813.

Christen, M., Kowalski, J., and Bartelt, P. (2010). RAMMS: Numerical simulation of dense snow avalanches in three-dimensional terrain. *COLD REGIONS SCIENCE AND TECHNOLOGY*, 63(1):1–14.

EN 1990 (2001). *Eurocode 0: Basis of structural design.* European Committee for Standardization.

JCSS (2001). *Probabilistic Model Code.* Joint Committee on Structural Safety JCSS.

Margreth, S., Stoffel, L., and Schaer, M. (2015). *Berücksichtigung der Lawinen- und Schneedruckgefährdung bei Seilbahnen.* WSL Institut für Schnee- und Lawinenforschung SLF, WSL Berichte, Heft 28.

Salm, B., Burkard, A., and Gubler, H. (1990). *Berechnung von Fliesslawinen: eine Anleitung für Praktiker; mit Beispielen.* Eidg. Institut für Schnee- und Lawinenforschung SLF, Mitteilung Nr. 47.

SIA 260 (2013). *SIA-Norm 260:2013: Grundlagen der Projektierung von Tragwerken.* Schweizerischer Ingenieur- und Architektenverein SIA.

SIA 269 (2011). *SIA-Norm 269:2011: Grundlagen der Erhaltung von Tragwerken.* Schweizerischer Ingenieur- und Architektenverein.

Wilhelm (1999). *Praxishilfe Kosten-Wirksamkeit von Lawinenschutz-Massnahmen an Verkehrsachsen : Vorgehen, Beispiele und Grundlagen der Projektevaluation.* Vollzug Umwelt. Bundesamt für Umwelt, Wald und Landschaft, Bern.