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DETERMINATION OF AVALANCHE MAGNITUDE AND FREQUENCY BY DIRECT OBSERVATIONS AND/OR WITH THE AID OF INDIRECT SNOWCOVER DATA

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Abstract

The limits of avalanche hazard in the terrain are determined by a combination of avalanche magnitude (runout distance, pressure) and avalanche frequency. The present study demonstrates with the aid of an avalanche-example, how direct avalanche records and indirect climatological snow data may be combined for the approximation of runout distances of 30-, 50-, 100-year return period. The methods of analysis are explained in detail whenever necessary for the formulation of the problems. The most often applied indirect method has some basic deficiencies: It is strictly speaking impossible to approximate a compound event(e.g. the runout distance of a 100-year avalanche) by indirect approximations based on a few components those respective conditional probabilities are unknown. Therefore it is recommended to spend more time on data analysis of direct avalanche observations, because such records enable us to calibrate the other indirect procedures.

Zusammenfassung

Gemäss den Richtlinien für die Lawinenzonenplanung müssen die Gefahrenzonengrenzen sowohl durch die Grösse (Auslaufstrecke, Druckwirkung) als auch durch die Frequenz der Lawinenereignisse abgesteckt werden. Im vorliegenden Bericht wird mit Hilfe eines Lawinenbeispiels gezeigt, unter welchen Umständen und wie direkte Lawinenbeobachtungen und indirekte klimatologische Schneedaten zur Bestimmung der 30-, 50-, 100-jährigen Auslaufstrecke dienen können. Die Berechnungs- und Schätzverfahren werden, soweit noch nicht allgemeiner bekannt, dargestellt und besprochen. Es wird gezeigt, dass die indirekte Methode grundsätzliche, wahrscheinlichkeitstheoretische Mängel aufweist und dass die geschätzte Anrisshöhe als auch die Anrissbreite der Lawine einen sehr starken Einfluss auf die Länge der Auslaufstrecken ausüben. Es wird empfohlen, den direkten Lawinenbeobachtungsreihen vermehrte Aufmerksamkeit zu schenken, da nur durch sie und ihre Analyse eine Eichung der benötigten Annahmen möglich ist.

1. Introduction and scope of study

The threat produced by large avalanches is determined by their frequency and magnitude. In contrast to other natural hazards, as earth quakes, floods, storms we do seldom dispose of long, well documented records on magnitude. The reason for this is partially based on the fact that there is no simply measurable quantity, which describes the magnitude of an avalanche in a given track. Nevertheless for design purposes (avalanche hazard maps, avalanche zoning) we badly need data on both in a few avalanches areas in order to establish general valid relationships between the two deciding quantities.

The guidelines for avalanche hazard mapping of various countries {cf. Schweiz. Oberforstinspektorat (1975)} have regard to avalanches of a certain mean return period (T), say avalanches of T:30, 100, 300 years, but apparently nowbody is in a state of visualizing the magnitude of such extreme events. Consequently, the concept of defining potential avalanche zones in terms of frequency (or return period) and possible avalanche magnitude (or dynamic pressure on a normally exposed wall) is not practicable.

The objective of this study is to provide through an example information on

1) how to analyze historical avalanche records in order to clarify the relationship frequency-magnitude;
2) the procedure of indirectly approximating the frequency and magnitude of avalanches by use of snowcover data (snowfall- and snowpack stability data);
3) the possibilities to combine statistical snowcover data and historical avalanche runout-distances in order to fix the limits of the various hazard zones (red, blue zone).

2. Historical avalanche records

In order to analyze the probabilistic pattern of large avalanche events in a given area or track, we need a few avalanche event-files, where date, location, size and some basic snow parameters are recorded. Despite of quite intensive search in handbooks, chronicles, old newspapers etc. it was not possible to find more than a few rudimentary historical files, suited for analysis.

Two such files, which have already been discussed in earlier publications (Föhn, 1975 and 1979) are represented in Fig. 1. It shows in graphical form the sequence of large avalanche events in two different tracks in the Davos area (Switzerland). We only concentrate on the lower half of Fig. 1, the so-called Salezertobel-avalanche. This avalanche, historically known since 1440 (cf. Laely (1951)) has been described for the period 1800 - 1975 by arbitrary magnitude units, whereby the lower threshold-magnitude M_1 1 means "at least minor barring of access-road to Davos". Only the fact that the important road to Davos has been obstructed from time to time through this avalanche gives us the possibility to visualize a crude relationship between avalanche magnitude and frequency. It is obvious that the beginning of the observation period of 175 years is not as well documented as the end and that some events are probably leaking in the file. Due to this it seems logical to procede to a shorter, but more thoroughly observed and documented observation interval of the same avalanche file, say the last 20 to 40 years before now. Before doing this, some general remarks and definitions on avalanches and their inherent design problem (avalanche mapping) have to be put forward.

Large avalanches start on rather steep slopes (28 - 45°), accelerate in general along their track and are finally stopped on the flatter valley-floor (0 - 15°). The avalanche path contains three specific areas: the starting zone, the track and the runout zone.

The upper part of Fig. 2 shows a cross-section and a map (1:10'000) of our example, the Salezertobel-avalanche.

The problem of avalanche mapping consists mostly in fixing in the runout zone by direct avalanche observations or by indirect approximations the maximum runout distance and the dynamic avalanche pressure (on a normally exposed wall) along the center line of the track. Whereas the first part of the problem: fixing maximum runout distances for an avalanche of a return period of 30, 100, years, might also be solved by direct observations, the second part (avalanche pressure) is only accessible by theoretical approximations.

The envisaged relationship between frequency (f{M}) or return period and magnitude (M) is different in every point of the avalanche track. However, as the lower part of Fig. 2 may document, this relationship must only be known in some specific points (e.g. P_o, P_1) along the track. The magnitude M of the avalanches has to be approximated by some directly observable quantities. Depending on observation conditions during the observation period avalanche-volume (V), -area (A), -length (L) or runout distance (s) may be envisaged.

3. Determination of relationship frequency/magnitude by direct observations (Salezertobel-avalanche)

Scanning the historical records of the Salezertobel-avalanche, reported in the "Winterbericht" (Eidg. Institut für Schnee- und Lawinenforschung, 1936 - 1979) it soon showed up, that only a few magnitude-quantities were extractable. Namely "avalanche length" (L) and consequently for the largest avalanches "runout distance" (s), starting from the point P_1, represented on Fig. 2.

Fig. 3a shows the relative frequency diagram f(L) of all avalanches (N=89) passing point P_o (cf. Fig. 2) in the time period 1950/51 - 1980/81. Because the starting line of these avalanches is situated sometimes at various altitude-levels, the given length is a relative one and not directly suited for further analysis.

3.1. Cumulative frequency analysis

Fig. 3b represents all avalanches (N=26) passing point P_1 and shows a cumulative frequency diagram F(s) of the recorded runout distances. This representation already has some practical relevance for our problem. The cumulative frequency F(s) yields us by definition

$$F(s) \quad \int_{o}^{\infty} f(s)ds \tag{1}$$

the percentage of cases, where the avalanche reached or surpassed a given point in the runout zone.

Furthermore, a more sophisticated frequency-magnitude or explicitly frequency-runout distance relation, may be found, following the ideas in an earlier paper (Föhn, 1979) and applying additionally a truncated exponential model to the data after Consentino & Luzio (1977).

The probability density function f(s) may then be formulated:

$$\begin{aligned} f(s) \quad & \frac{\beta \exp\{-\beta(s-s_1)\}}{1-\exp\{-\beta(s_p-s_1)\}} && \text{for } s_1 \leq s \leq s_p \\ f(s) \quad & o && \text{for } s \geq s_p \end{aligned} \tag{2}$$

where s_1 is the lower threshold value of the runout distance in P_1; β is a scale parameter, and s_p is the truncation distance representing the upper limit permissible on physical grounds.

Integrating equation (2) we obtain again the probability (P) that an avalanche will have a runout distance equal or greater than a given value:

$$P(s_i \geq s_1) \quad F(s) \quad \int_{s_1}^{s_p} f(s)ds \quad \frac{1-\exp\{\beta(s_p-s)\}}{1-\exp\{\beta(s_p-s_1)\}} \tag{3}$$

with the same limitations as given for (2). With the aid of the stepped, cumulative frequency values of Fig. 3b the scale parameter β may be approximated. Its value amounts for the given track to $\beta \approx 3$. Using this value, a truncation distance of s_p 1.1 km and equation (3) the smooth, theoretical curve of Fig. 3b has been calculated.

Now we are in a state of approximating the annual probability or return period of a given recorded runout distance, whereby $\{p(s) \quad \frac{1}{T(s)}\}$.

First we approximate the mean annual probability (α_{s1}) of surpassing the threshold distance s_1 with the aid of the annual observations in the given observation period (31 years):

$$\alpha_{s1} \quad \frac{26 \text{ events}}{31 \text{ years}} \quad 0{,}84$$

Then by use of the equation:

$$p(s) \quad \alpha_{s1} \quad F(s), \tag{4}$$

we calculate the annual probability p(s) or the return period T(s) that a given runout distance lies between s_1 and s_p according to equation (3). For the distance of 1 km, we get:

$$p \quad 0.84 \quad 0.0134 \quad 0.011; \qquad T \quad \frac{1}{0.011} \approx 90 \text{ years.}$$

By iteration we may calculate for our track the "once-in-a-century" runout distance, which amounts to 1.03 km. Analogously the 30-year avalanche would stop at $\approx$ 0.83 km. Because these results are biased by setting subjectively an upper threshold value s_p, we also take aim at others methods.

3.2. Extreme-value statistics

The problem of determining the runout distance of a 100-year avalanche in a given track may even better be solved by the statistical theory of extreme values of Gumbel (1958). These methods of data analysis which use only the largest or smallest values from sets of data have the following advantages:

1) only the largest (smallest) values have to be known in aequidistant intervals (e.g. per year);
2) the methods are distribution-free, i.e. any kind of data with unknown probability distribution may be analysed as long the density function f(x) converges to zero for large values of x;
3) the methods are well established (statistical moment-calculations) and the probability of annual maxima may be accomplished either analytically or graphically (probability paper);
4) the methods integrate by its inherent properties also extreme values, which have not yet been recorded. This is most desirable in predicting expected future performance.

Without going into details of the method, we may approximate the probability $P(s_i \geq s)$ according to Gumbel (1958) as:

$$P(s_i \geq s) \quad (1-F(s))^n \tag{5}$$

where n denotes the number of extremes, which in our case is identical with the number of years in the observation period. Furthermore we may write:

$$F(s) \quad \exp\{-\exp^{-a(s-b)}\} \quad \text{for } \begin{array}{l} a > o \\ s \geq o \end{array} \tag{6}$$

and $$T(s) \quad \frac{1}{P(s_i \geq s)} \approx \frac{n+1}{m} \tag{7}$$

The term "a" is a positiv empirical parameter, b denotes the mode of the density function and m finally stays for the rank of the extreme values, grouped in descending order from 1 to n. The term $\frac{n+1}{m}$ yields directly the plotting position of the individual values on extreme value probability paper.

The outlined analysis has been performed with our runout distance extreme values (per year) and the graphical result is given in Fig. 3c.

The greatest advantage of the extreme-value method is due to the fact that extreme values per year are more often observed and therefore rather extractable from historical avalanche records than all values beyond a given threshold. Whereas the cumulative frequency analysis in our case could only be based on 31 years, the extreme-value statistic contains now 45 years, (1936/37 - 1980/81).

The 100-year avalanche has a runout distance of 1.11 km, the 50-year avalanche reaches at 0.94 km and the 30-year event would stop at s $\approx$ 0.82 km. It may be seen from Fig. 3c, that only 25 values are plotted. This is due to the fact that the rest of extreme events per year (45 - 25   20) are "zero-events", that means the avalanche did not reach in these years the point $P_1(s=o)$. The "zero-events" have not been taken into account in the curve fitting procedure, because Gumbel (1958) explains: "If we are interested in large return periods, we may safely consider only the set of largest values and need not take into account all values which exceed the basic stage,

Summing up, we may say that the historical data file and the two outlined methods of analysis allowed in this case to answer the long lasting question to which recorded runout distance we have to assigne a certain frequency or return period.

4. Determination of frequency/magnitude relationship by indirect snowcover/terrain analysis (Salezertobel-avalanche)

Avalanche mapping and therefore determination of the limits of the runout zone for 30-, 100-, 300-year avalanches has to be executed most often in areas where no or very scarce direct avalanche data are available. It seems logical to procede to indirect methods: estimating by climatological snow cover records, snow stability evaluations and terrain characteristics the probable (T 30-, 100-, 300-years) avalanche mass or volume in the starting zone and predicting the runout distance and pressure by use of criteria pertaining to avalanche dynamics. Whereas the basis for the avalanche dynamic part of the problem has been developed some 25 years ago first by Voellmy (1955) and consecutively refined by others {Salm (1972, Schaerer (1974), de Quervain (1975), Buser & Frutiger (1980)}, little is known about the first part. The authors will concentrate on this first part and hope to contribute some essential points to further discussions.

4.1. Estimation of starting zone snow volume

4.1.1. General remarks

Direct observations on starting zone snow volume which breaks loose to form an extreme avalanche are so scarce, that only indirect snow cover and terrain studies may be envisaged. We are faced with the unconfortable task to estimate the avalanching snow volume e.g. of a 100-year event not knowing his runout snow characteristics, runout flow depth nor snow cover depth and structure in the starting zone.

The 100-year avalanche (or his runout distance) is a composite event originating from many singular probability density functions, e.g. the ones of b_o (starting zone width), d_o (starting zone snow depth), R (hydraulic radius of flow), ρ (snow density), ξ (turbulent friction coeff.), μ (basic friction coeff.). The complexity of the problem may be demonstrated by enumerating the most important variables for runout distance approximations: s f (d_o, b_o, ξ, μ, b',···) whereas b' stays for the runout zone avalanche width. Because all variables are dependent on each other the probability of the compound event, e.g. the runout distance of the 100-year avalanche $\{Pr(s_{100y})\}$, had to be approximated by multiplication of many unknown conditional probabilities:

$$P_r(s_{100y}) \quad P_r(d_o) \quad P_r(b_o/d_o) \quad P_r(\xi/d_o b_o) \qquad (8)$$

It is now obvious, that our usual indirect method first estimating the 100-year starting zone snow depth (d_o) would imply that all other conditional probabilities must be one in order to achieve for the compound event a probability of 0.01.
This means that all other "variables" were constant, a demand which seems not very logical.
Although we have basical difficulties to approximate indirectly our 100-year avalanche or runout zone as compound event, we follow the lines of the indirect method in order to compare these runout distances with the ones resulting from direct runout zone observations.

4.1.2. Snow depth (height) of snow slab

Necessary assumptions:
- Extreme avalanches start as slabs,
- during or shortly after large, dry snowfalls,
- the old snowcover does not break loose
  snow layer stability conditions are similar as in the case of smaller, usual snow slabs and may be approximated by the Coulomb-Mohr failure criterion
- snow depth (height) on sloping terrain corres-

ponds to the climatological values recorded on level plots.

The procedure and the philosophy of calculating a 100-year snowfall-height has been described in an earlier publication, cf. Föhn (1978), thus we directly determine this height in our example (Davos area)as $\Delta HS = 1.9$ m from Fig. 4a.

The snow slab height (h_o) will be determined by Fig. 4b. There by use of empirical cohesion values (c) described in an earlier investigation (Föhn, 1981) and by applying the Coulomb-Mohr criterion to the potential glide layers we have calculated a potential snow slab height (h_o) as $f(\psi_o)$:

$$h_o \quad \frac{c \cdot \cos\phi}{\rho\cos\psi_o\sin(\psi_o-\phi)} \tag{9}$$

where ϕ stays for the internal friction angle of the glide layer and ψ_o is the mean slope angle of the starting zone areas.

We see from Fig. 4b and 2 that to the uppermost starting zone area ($\psi_o \approx 37^o$) a slab height of 1.45 m and to the lower ones a height of 1.65 m, 1.9 m respectively has to be attributed.

4.1.3. Starting zone area of snow slab

According to the general remarks in Section 4.1.1. we do not dispose of any mean to estimate the 100-year starting zone area or width. Not knowing the combinative effects on the final result, it wouldn't much improve the situation anyway.

Starting zone areas or width are estimated with the aid of a map (preferably 1:10'000) and the basic knowledge that slopes of inclination $\psi_o < 30^o$ will seldom fail as snow slabs.

Fig. 2b shows the starting zone areas in our example.

4.2. Calculation of runout distance (indirect way)

Using the basic formulas of avalanche dynamics, assembled by de Quervain (1975) and the newly published friction terms (μ and ξ) from the work of Buser & Frutiger (1980), we are able to approximate the runout distance. It amounts to 0.93 - 1.03 km according to varied initial conditions and assumptions. - We have to remember that our once-in-a-century runout distance determined directly by extreme-value statistics was s 1.11 km. So what? - Does this difference mean that our initial hesitations to follow the indirect way are fully justified? - In order to clarify this point, we decided to put the cart before the horse and to recalculate the most critical starting zone variables backwards with the aid of known runout distances.

5. Sensibility analysis of starting zone variables in relation to runout distances

The flow equations of avalanche dynamics obey between the end of the starting zone and the beginning of the runout zone the condition of mass continuity. This circumstance enables us to calculate backwards the starting zone variables (d_o, b_o) for a avalanche of given runout distance and corresponding frequency (or return period).

Runout zone begins there, where tg ψ_u $\mu \approx 0.16$. This condition forced us to redefine our previous runout distance s, which has been used to assemble the observed runout distances. The redefined runout distance s', starting at P_1' in Fig. 2 and 5 may be written:

$$s' \quad s-0.4 \quad \{km\} \tag{10}$$

If we denote the discharge volume at P_1' with Q_1' and the one at P_o with Q_o, we can formulate:

$$Q_1' \quad Q_o \tag{11}$$

and further

$$Q_o \quad d_o \cdot b_o \cdot v_o \quad b_o\{d_o{}^3\xi(\sin\psi_o - \mu_o\cos\psi_o)\}^{1/2} \tag{12}$$

and

$$Q_1' = d' \cdot b' \cdot v_1' \quad b'\{d'^3\xi(\sin\psi_1' - \mu_1\cos\psi_1')\}^{1/2} \tag{13}$$

The terms v_o, v_1' describe the velocities in the corresponding track points. Assuming $\mu_o \quad \mu_1$ we substitute (12) and (13) in (11) and solve for d_o, the snow slab depth:

$$d_o \quad d'(\frac{b'}{b_o})^{2/3} \left\{\frac{(\sin\psi_1' - \mu\cos\psi_1')}{(\sin\psi_o - \mu\cos\psi_o)}\right\}^{1/3} \tag{14}$$

By use of the basic runout distance equation:

$$s' = \left[R\xi\Phi/\{-2g\Phi_u + 10g^2R\Phi/(10gd' + R\xi\Phi)\right]\cos\psi_u \tag{15}$$

where d' is the avalanche flow depth, $\Phi \quad (\sin\psi_1' - \mu\cos\psi_1')$, $\Phi_u \quad (\sin\psi_u - \mu\cos\psi_u)$, $g \quad 9.81\ m/s^2$ and $R \quad \frac{b'd'}{b'+2d'}$, we may find by iteration an empirical function between d' and s' for our example:

$$d' \quad 0.0107(s')^{1.029} \tag{16}$$

The width b' of the runout zone has been fixed on observational basis to 150 m and ψ_1', ψ_u are 16^o, 6^o respectively.

Replacing the term d' in equation (14) through equation (16) and introducing $h_o \quad d_o/\cos\psi_o$ yields us a new equation which shows the almost linear dependency of the snow slab height h_o on the runout distance s'

$$h_o \quad \frac{1}{\cos\psi_o}\left(\frac{b'}{b_o}\right)^{2/3}\left(10^{-2}(s')^{1.03}\right)\left[\frac{\sin\psi_1'-\mu\cos\psi_1'}{\sin\psi_o-\mu\cos\psi_o}\right]^{1/3} \tag{17}$$

Keeping the runout width b' constant at 150 m and introducing b_o (width of starting zone) and ψ_o (slope angle) as additional parameters, we may calculate the plotting points for our "sensibility-diagram", given as Fig. 5.

This Figure demonstrates that the runout distance s is strongly dependent on h_o and b_o in an almost linear fashion but that the starting zone slope angle ψ_o is of minor influence. Figure 5 yields us finally the test for the validity of the indirect approach (climatological snow data - snow stability - avalanche dynamics) in runout distance calculations. In chapter 4.2 we have seen that our indirectly calculated maximum runout distance was almost 100 m shorter than the one based on historical records. Tracing these difference back to the starting zone variables (h_o, b_o, ψ_o) with the aid of Fig. 5 we see, that a mean slab height approximation 0.3 m too short <u>or</u> a total slab width 130 m too narrow <u>or</u> a combination of 0.15 m shorter slab height and 100 m narrower slab width could already cause such differences. Keeping this and the fact in mind that other terms may also be error-loaded (e.g. ξ, μ, d') we feel that the outlined procedures yield reasonable results. However future field measurements and corresponding analysis are needed and should concentrate on the rather unknown relationship: starting zone width/snow slab height in order to improve this situation.

6. Conclusions

The present study shows that:

- direct avalanche records may yield by appropriate statistical analysis (cumulative frequency analysis or extreme value-statistics) the 30-, 50-, 100-year runout distances. Such runout distances are a prerequisite for checking in a given region the validity of the indirect approach;

- the outlined quantitative procedure to estimate the snow slab dimensions seems reasonable in view of the thereof calculated runout distances. It contains three steps:
  1) determination of the 100-year snowpack increment layer by snowfalls in an area,
  2) evaluation of the maximum possible snow slab height by the Coulomb-Mohr criterion and empirical snow strength values,
  3) approximation of the most likely snow slab area with detailed maps;
- the independent approximation of the 100-year runout distance on an example by the direct and indirect method demonstrates clearly the need for such calibration examples. It also shows that the starting zone dimensions, despite of reasonable approximation methods, have to be studied in more detail with field measurements. A 10 %-error in starting zone width and snow slab height causes in the case of small starting areas the resulting avalanche to run up to 100 m longer or shorter than with "correct" values. Such differences are too large to be accepted in fixing the avalanche zone limits.

7. Literature

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Fig. 1: Two historical avalanches observed in the valley-floor of Davos with arbitrary magnitude units (acc. Föhn 1979)

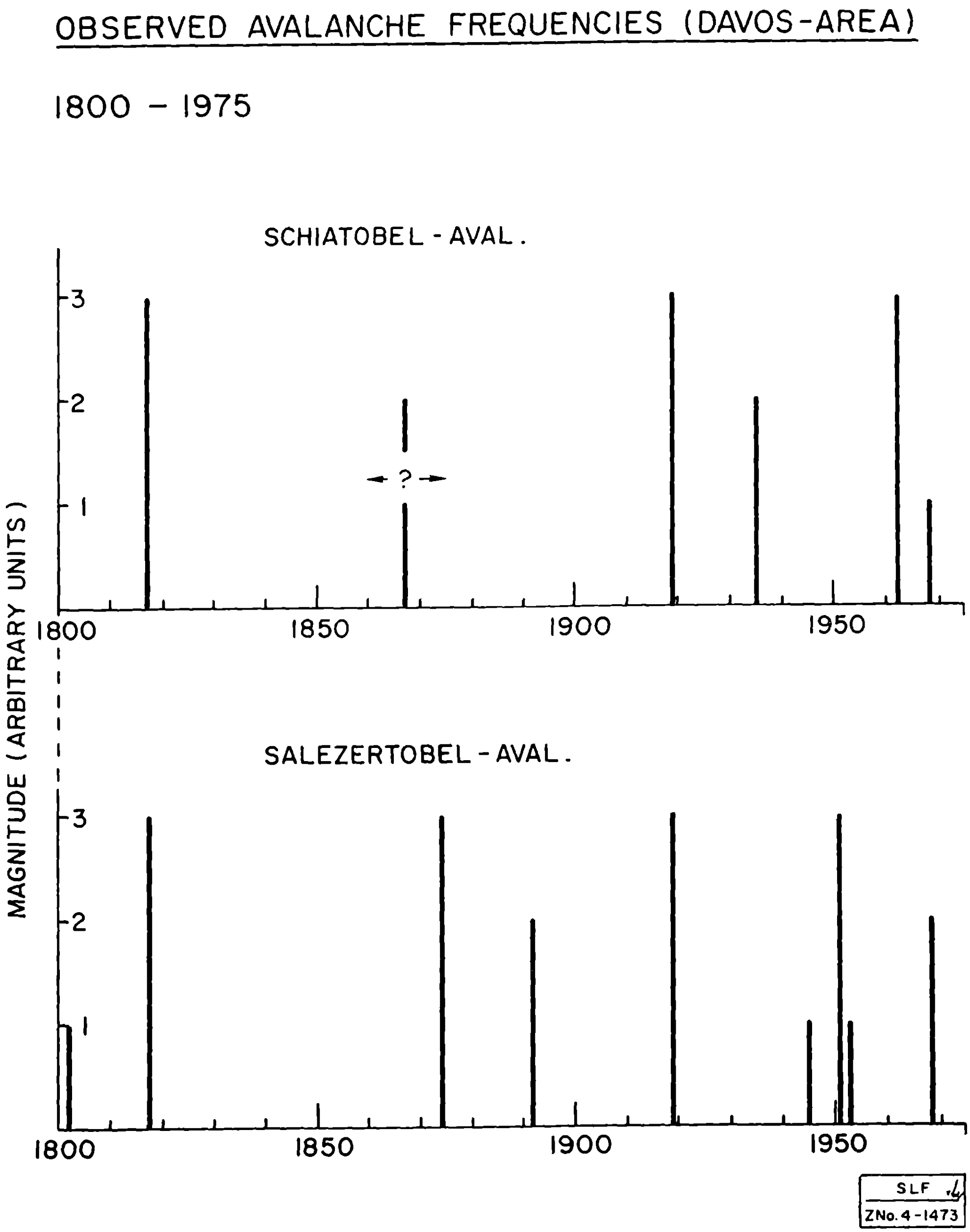


Fig. 2a): Map of Salezertobel-avalanche path (Davos)

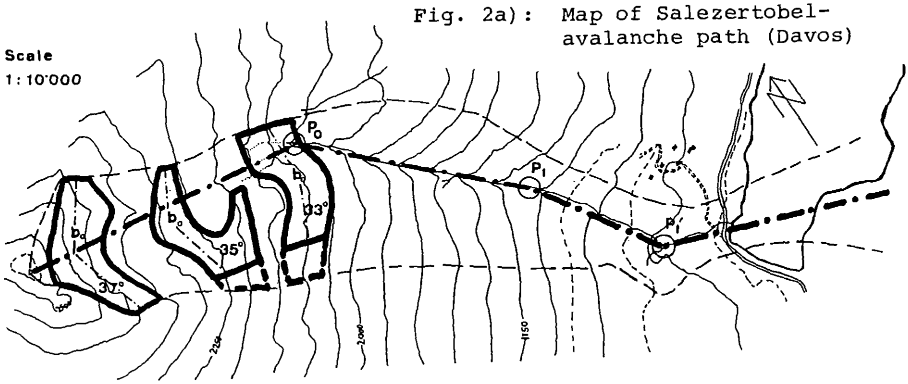


Fig. 2b): Cross section of Salezer-tobel-avalanche path

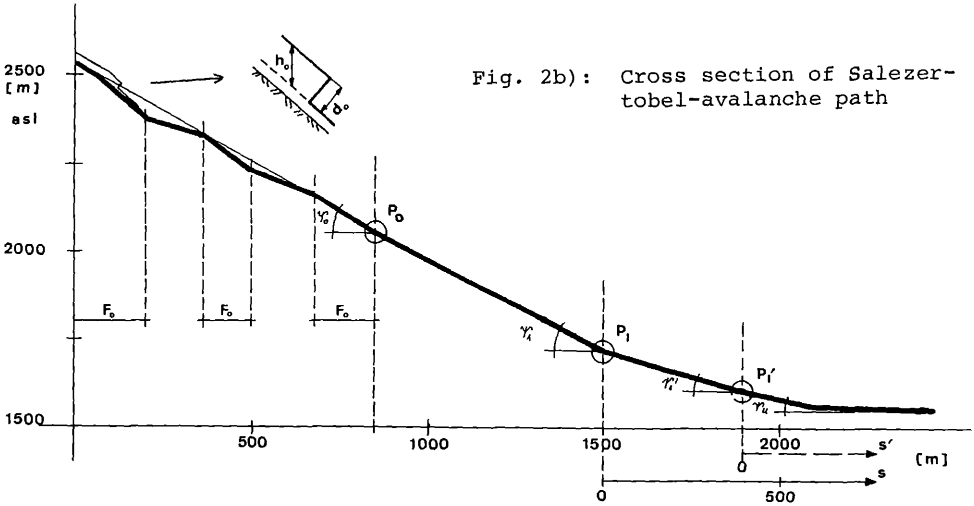
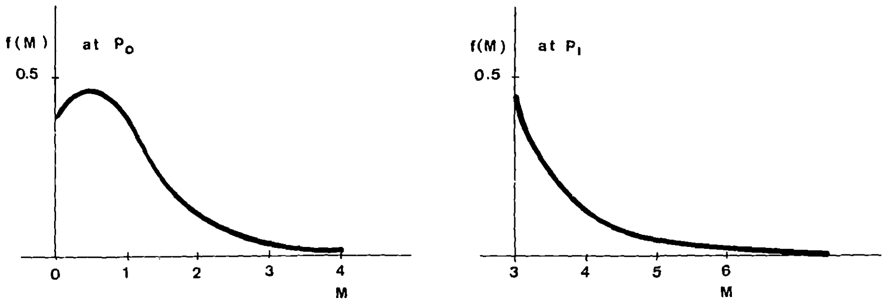


Fig. 2c): Relationship between magnitude and frequency at point P_o and P_1



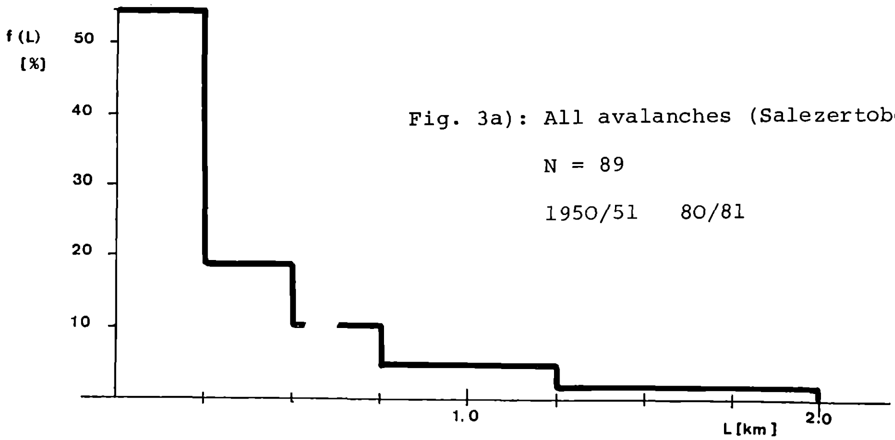


Fig. 3a): All avalanches (Salezertobel)

N = 89

1950/51 80/81

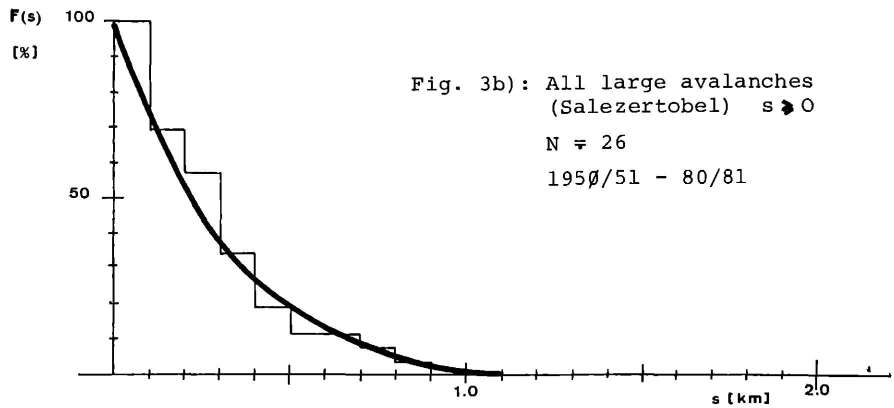


Fig. 3b): All large avalanches (Salezertobel) s ≥ 0

N ∓ 26

1950/51 - 80/81

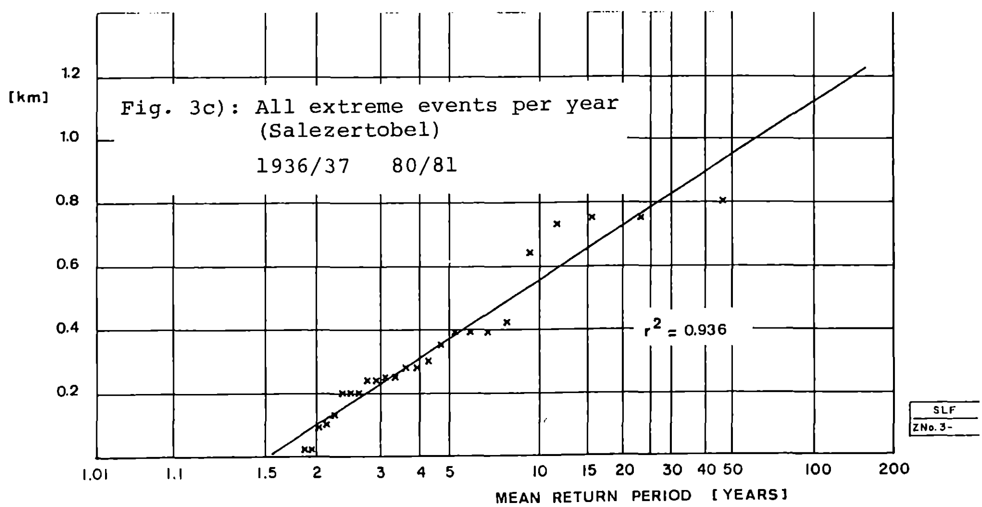


Fig. 3c): All extreme events per year (Salezertobel)

1936/37 80/81

Fig. 4a): All extreme values of Snow cover increments ΔHS per year at Weissfluhjoch (1936/37 - 80/81)

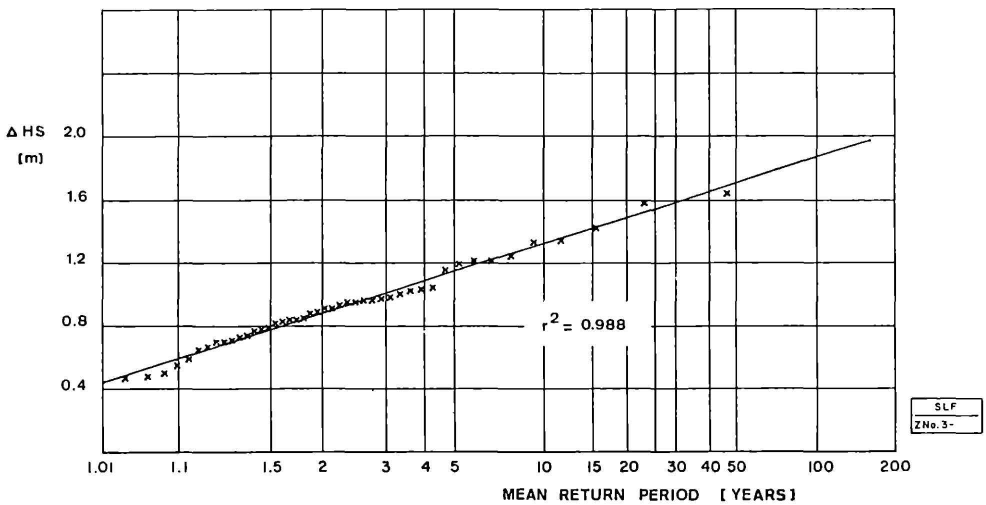


Fig. 3b): Relationship between slope angle (ψ_o) and snow slab height (h_o)

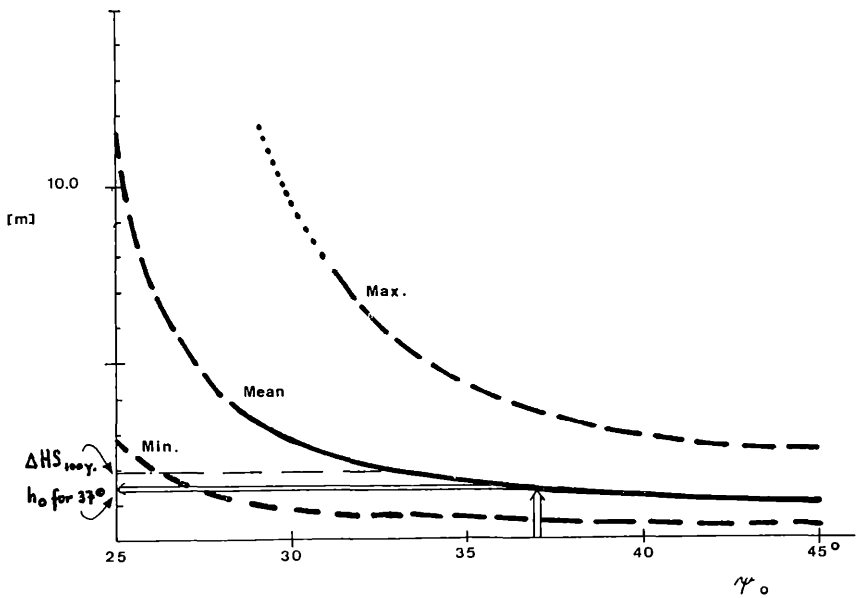


Fig. 5): Relationship between runout distance s (or s') and snowdepth of snow slab (h_o) for various starting zone width (b_o) and various slope angles (ψ_0)