STATISTICAL RUNOUT MODELING OF SNOW AVALANCHES IN THE CATALAN PYRENEES

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ABSTRACT: In the present study, the statistical runout regression model α-β was applied in order to update equations obtained 20 years before in the Catalan Pyrenees. This was carried out by including the knowledge of major avalanche activity in this region and by using the current mapping tools. The model was obtained from a dataset constituted by 82 avalanches with an estimated return period of 100 years (T100). General and specific equations were obtained for different types of avalanche path morphologies. The new, updated equations show a good agreement with those obtained previously. However, 23% of the T100 avalanches did not reach the beta point, for which the α-β model could not be applied. The β point is the point on the avalanche profile, at the top of the runout zone, where slope reaches 10º and the model assumes that the avalanche should exceed it. To find out the parameters that could explain why there are avalanches that do not reach the β point we applied a logistic regression analysis. The size of the starting zone (small and very small starting zones), and their aspect (northwest) were the most powerful parameters to explain the non-arrival to the beta point. These results can be related with the known, low frequency major avalanche cycles that occur in the regions where these avalanche paths are located. Probably, T100 major avalanche cycles in these areas do not provide conditions sufficiently optimal to develop avalanches large enough to accomplish with α-β model requirements.

KEYWORDS: Avalanche, statistical modeling, regression model, logistic regression model, Pyrenees.

1. INTRODUCTION

The determination of avalanche runout distance is fundamental for avalanche hazard mapping in urban planning. One tool, among others, to calculate this parameter are the statistical models.

The statistical models allow to obtain the runout distance along a topographic profile of the avalanche path. The model is constructed by using a representative set of avalanche events whose runout is known. The two most widely used statistical models are the α-β model (Lied and Bakkehoi, 1980) and the Runout Ratio model (McClung et al., 1989).

The regression model α-β was developed by Lied and Bakkehoi (1980) with data from 192 avalanche paths in Norway with very well defined runout distances. They found that β was the only significant predictor and, since then, α-β models have been obtained in other mountain ranges in Europe, North America and Japan.

Furdada (1996) and Furdada and Vilaplana (1998) applied the regression model α-β for the first time in the Pyrenees. The work was done using the means available at that time: 1: 50.000 topographic maps (DEMs were still a very incipient tool), and avalanche data obtained in the first cartography campaigns that were carried out to feed the avalanche cadastre of Catalonia, precursor of the Avalanche Database of Catalonia (BDAC, Oller et al., 2005), nowadays maintained and updated by the Cartographic and Geological Institute of Catalonia (ICGC). They obtained 4 regression models according to the morpho-topographic characteristics of the terrain profile. For future work, they recommended (i) improving the avalanche cadastre to work with more reliable data, (ii) improving the accuracy of topographical bases and (iii) the use of digital terrain models.

Since the work of Furdada (1996) there have been important advances in digital cartography (topographical bases, high resolution DEM, digital orthoimagery), and also in the knowledge of avalanche dynamics in the Catalan Pyrenees with the elaboration of the Avalanche Paths Map (Oller et al., 2006), the implementation of the Avalanche Database of Catalonia (BDAC-ICGC; Oller et al., 2005), and the improvement of the knowledge about dynamics of major avalanche cycles (Muntán et al., 2009, García et al., 2010, Oller et al., 2015). All these advances led us to

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consider an update of the results obtained by Furdada and Vilaplana (1998).

During the preparation of the data set, we realized that not all the avalanches that we considered T100, reached the β point. These events (a 23%) were analyzed separately to analyze this fact.

Taking into account this context, the present study aims (i) to update the α-β model for the Catalan Pyrenees, based on the cartographic tools currently available and the current knowledge of avalanche dynamics in this area, (ii), to analyze the factors that have influence on the runout distance considering the morphometric and dynamic characteristics of the avalanches of the dataset, and (iii), to identify the factors that have the greatest influence on the fact that the avalanche does not reach β point.

2. STUDY AREA

The study area corresponds to the Catalan Pyrenees, which are located at the southeast of the Pyrenees mountain range (Figure 1). In this area, three climate varieties (García-Sellés et al., 2007) and Major Avalanche Nivological Regions (MANR; Oller et al., 2015) were defined. The north-western part has a humid oceanic climate with regular winter precipitation. Towards the south, the weather gains continental traits, and winter precipitation decreases. In the eastern Pyrenees the Mediterranean influence takes predominance; winter precipitation increases though irregularly distributed.

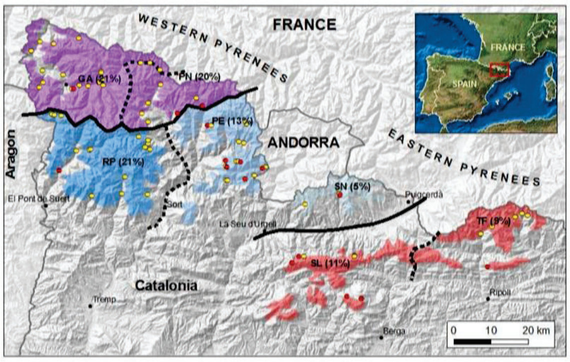

Figure 1: Study area. MANR (Major Avalanche Nivological Regions): GA (Garona), PN (Pallaresa Nord), RP (Ribagorçana - Pallaresa), PE (Pallaresa Est), SN (Segre Nord), SL (Segre - Llobregat), TF (Ter - Freser). Colored areas correspond to the areas susceptible to avalanche activity. Violet tones: MANR with oceanic influence. Blue tones: MANR in the transition zone. Red tones: MANR with Mediterranean influence. The intensity of the color indicates the frequency of occurrence of Major Avalanche Cycles (MAE) (% in brackets). Dots correspond to avalanche events from which the present work has been carried out. Yellow: the avalanche reach the β point. Red: the avalanche doesn't reach the β point.

3. MATERIAL AND METHODS

3.1 α-β model

In Figure 2, the main parameters used for the application of the α-β model are plotted. H, β, θ and y" have proven to be useful in regression models for estimating runout maximums (α) in mountain regions around the world.

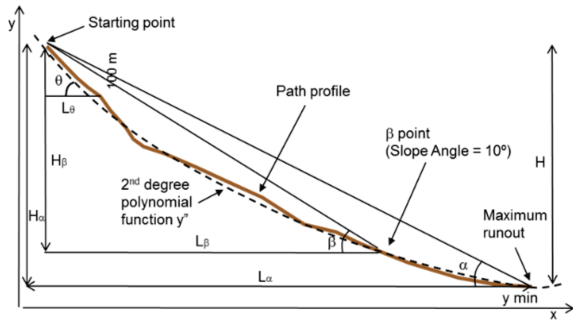

Figure 2: Main parameters of the α-β runout model (after Lied and Bakkehoi, 1980).

Bakkehoi et al. (1983) demonstrated that β is the parameter that best predicts run-out distance and that multiple regression analysis does not imply a significant improvement of the model based only on β.

3.2 Major avalanche database

Major avalanche data (avalanches that exceeded the size of usual avalanches; Schaerer, 1986) used for this work come from a Major Avalanches Database (MADB). Information stored in this database comes from the BDAC-ICGC), and from additional search performed by the authors through field work, inquiries to witnesses and photointerpretation. The BDAC sources of information and stored data characteristics are described in detail in Oller et al. (2015). The MADB compiles information concerning major avalanche occurrence: release date and snow and weather conditions, morphometries, flow characteristics and damage. At present the MADB stores 897 major avalanches (MA), mapped in 551 avalanche paths.

For the purpose of the present work, those MA with an estimated return period of 100 years (T100) were selected (155 events, corresponding to the 19% of the data set). The selected avalanches had to accomplish the necessary requirements for the α-β method: minimum vertical drop of 350 m, terrain profile without run up or irregularities in the runout area, differentiated and unique starting zone, and not having been modified anthropically (Sinikas and Jamieson, 2014).

Such limitations reduced the data set to 82 T100 avalanche events. These events are homogeneously distributed in the study area (Figure 1), and occurred mainly during the XX and XXI century.

Table 1: Descriptive statistics of the topographic and morphometric parameters considered, and correlation with the response variable α.

Variable	N	Mean	SD	Range	R^2	P value
α (º)	82	25,2	3,5	18,5-34,0	-	-
β (º)	65	26,9	3,8	19,7-36,1	0,765	0,000
θ (º)	82	34,2	4,0	25,3-43,1	0,069	0,017
y'' (m^{-1})	82	0,0003	0,0002	0,0000-0,0008	0,060	0,026
Hα (m)	82	872	287	300-1665	0,001	0,760
Lα (m)	82	1888	683	541-3562	0,169	0,000
Azs (Ha)	82	6,17	5,67	0,38-24,68	0,050	0,044
Ozs (º)	82	201,4	101	2-360	0,042	0,063

For the selected avalanches, we obtained the morphometric parameters that have the greatest influence on α: β, H, y'' and θ (Figure 2). In addition to the aforementioned parameters, other parameters were measured which were also considered that could have influence on the runout distance as the shape of the topographical profile of the avalanche path (PT), the area of the starting zone (Azs), the aspect of the starting zone (Ozs), the confinement of the avalanche (Can) and the climatic region to which the avalanche path belongs (Cli), as applied by other authors (Furdada and Vilaplana, 1998; Jones and Jamieson, 2004). Another parameter that we considered is the forest extent devastated by the avalanche, since in many of the registered avalanches it was very important. Unfortunately, this data was not possible to measure for the whole set of data and this variable was not considered.

The topographical profile (PT) was classified in linear/planar (1), concave (2), and hockey stick (3), according to Jones and Jamieson (2004). We add a new class, irregular (4), for the profiles not corresponding to the previous shapes. The area of the starting zone (Azs) considered in each avalanche path, was measured on the horizontal projection. The mean aspect of the starting zone (Ozs) of each avalanche path was measured in degrees. The confinement (Can) was classified into four classes, based on the transition between the track zone and the runout zone, in non confined–non confined (1), non confined–confined (2), confined–non confined (3) and confined–confined (4). The climate region (Cli) in which the avalanche path is located was assigned to each avalanche path: Oceanic (1), Transition (2) and Mediterranean (3).

4. ANALYSIS AND RESULTS

4.1 *Application of the α-β model*

Table 1 shows how only β has a good correlation with α. For the rest of the measured parameters correlation is very poor. Taking this into account, we used only the variable β for the regression with α.

Given the limited set of data, in a first stage, a general model was constructed. To do this, we separated the events that do not reach the β point, 19, leaving a set of 63 events. We selected 10 avalanches from the data set (16% of the data set, homogeneously distributed throughout the study area) in order to apply later the model and to check and validate its reliability.

From the remaining 53 avalanches, the regression equation 1 was obtained.

$\alpha=0{,}85\beta+2.10°$ $R^2=0{,}76$ $S=1{,}87°$ $N=63$* (E. 1)

*Includes the 16% of the events for validation.

The coefficient equation shows a positive correlation between parameters and R^2 indicates that 76% of the α is explained by the independent parameter β, which is very large.

The model was then applied to the 10 previously selected avalanche events. The values obtained were located within the 95% confidence interval, which indicates a satisfactory fit of the model.

Applying the general equation obtained by Furdada and Vilaplana (1998; $\alpha=0{,}97\beta-1{,}20°$ $R^2=0{,}87$ $S=1{,}74°$ $N=216$) to the 63 selected avalanches, and comparing the results with the one's obtained in the present study (Table 2), differences in mean α angles were negligible.

Table 2: Differences between the results obtained applying the function obtained in this study and the one obtained by Furdada and Vilaplana (1998).

	This study (mean±SD)	Furdada & Vilaplana (1998) (mean±SD)
Mean α (º)	24,98±1,87	24,91±1,74

The comparison of the results obtained in both models indicate that they are in the same range of magnitude and always within the range of the standard deviation. It indicates that the dataset used by Furdada (1996) would be in the range of

T100, the same return period of the events used in the present work. On the other hand, the topography base 1:50.000 used in their work, should not be a limitation, given the similar results.

4.2 Avalanches that do not exceed the β point

The previous treatment of the data revealed that 19 events (23% of the data set) do not reach the β point. In the same way than the other 63 avalanche events, these are the largest avalanches ever observed in their respective avalanche path during the XX and XXI century. These avalanches accomplish the conditions established by McClung and Lied (1987), and therefore they should overpass the β point.

Table 4 shows the values obtained for these avalanche paths, compared with those that reach the β point. The size and orientation of the starting zone, the confinement, and the climatic zone are the variables that present the greatest differences with respect to the set of avalanches that do exceed β.

Table 4. Descriptive statistics of the main topographic and morphometric parameters of avalanches that do not exceed the β point (left), and exceeding the β point (right).

	Avalanches don't reach β				Avalanches reach β			
Variable	N	Mean	SD	Range	N	Mean	SD	Range
α (º)	19	26,5	2,6	22,1-33,0	63	24,8	3,6	18,5-34,0
θ (º)	19	33,4	2,5	29,2-39,6	63	34,4	4,3	25,3-43,1
y'' (m^{-1})	19	0,0003	0,0001	0,0001-0,0006	63	0,0003	0,0002	0,0000-0,0008
Hα (m)	19	808	298	300-1289	63	892	283	377-1665
Lα (m)	19	1643	647	541-2840	63	1962	680	802-3562
PT	19	1,7	0,5	1-2	63	1,2	0,8	1-4
Azs (Ha)	19	3,46	3,38	0,38-11,52	63	6,99	5,97	0,49-24,68
Ozs (º)	19	271	85	54-360	63	180	97	2-358
Can	19	3,3	1,2	1-4	63	2,8	1,2	1-4
Cli	19	2,2	0,7	1-3	63	1,7	0,7	1-3

4.3 Application of the Logistic Regression

We applied the Logistic Regression to explain why there are avalanches that do not reach the β point. This technique was applied because it is one of the most appropriate method when dichotomous variables are analysed (to reach, or not to reach β).

To apply the logistic regression, and taking into account the reduced number of data, continuous variables and categorical variables were transformed into dichotomous variables.

The results of the model (table 5) show that Aspect of the starting zone (Ozs), and Area of the starting zone (Azs) are significative with a p value lower than 5% (significant level), indicating their association with the probability to reach the β point. That means: (i) avalanches coming from starting zones oriented to NW have a 85,5% less probability to reach the β point than avalanches with SE facing starting zones; (ii) avalanches coming from small and very small starting zones have a 66% less probability to reach the β point than avalanches coming from medium to large starting zones; and (iii) the obtained function is more sensitive to identify avalanches that do not reach the β point (82,4%) with respect to those that reach this point (61,5%).

Table 5. Results of the logistic regression analysis (equation variables).

	B	Wald	Sig	Exp (B)	95% CI EXP(B)	
					Lower	Upper
Azs	-1,080	5,057	0,025	0,340	0,133	0,870
Ozs	-1,933	17,900	0,000	0,145	0,059	0,354
Constant	1,745	19,043	0,000	5,728		

The goodness of fit and discrimination ability of the logistic regression model are confirmed by the area under the estimation ROC curve (AUC) with a value 0,766.

5. CONCLUSSIONS

A data set with 82 T100 avalanches has been used for the update of the α-β model in the Catalan Pyrenees. The morphometry of these avalanches revealed that a 23% of the events do not reach the β point.

A general equation of the regression model α-β has been obtained from the 63 T100 avalanches that reach the β point. The results are in a similar range of magnitude, and always within the range of the standard deviation that the one's obtained by Furdada and Vilaplana (1998). This indicates that the dataset used by these authors would correspond to a similar return period. The improvement of the topographic information used for the present work has not represented significant improvement of the results.

The analysis of the influence of other terrain variables on the run-out distance shows that they are not statistically significant.

The application of Logistic Regression has allowed to identify the parameters that better explain the avalanches than do not reach the β point, and to quantify the probability that the avalanche reaches this point. The parameters that influence are aspect and area of the starting zone. Avalanches coming from starting zones oriented to NW have a 85,5% less probability to reach the β point than avalanches with SE facing starting zones. Avalanches coming from small and very small starting zones have a 66% less probability to reach the β point than avalanches coming from medium to large starting zones.

The reason why avalanches do not reach the β point can be explained, on the one hand, by the imprecision in the assignation of the return period to the avalanche event. On the other hand, It can be due to a low frequency of Major Avalanche Episodes (MAE) that generate avalanches in northern slopes in Transition climate zone. In these regions, advections that generate MAE mainly in northern slopes represent only the 18% of MAE. It is possible that these MAE do not generate the conditions to develop avalanches large enough to reach β, as it would be expected, according to McClung et al. (1989). The large forest extension that grow in these low frequency avalanche paths, we believe that should also have influence on the runout distance, but this parameter could not be analyzed in this study.

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