FULL SCALE FIELD TESTS ON ROCKFALL IMPACTING TREES FELLED TRANSVERSE TO THE SLOPE

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ABSTRACT

To compensate for the temporary loss of protection due to the reduced forest stand density in the felling area, a considerable part of the trees felled in rock fall protection forests are left in place. Although being a widely used technique, there is little objective information on the efficacy of these trees felled transverse to the slope.

To quantify the protective function of such structures, full scale rock fall tests on a protective structure made with trees felled transverse to the slope were carried out. The results show significant energy losses when impacting the structure. However, the rock energy significantly increases again after the structure if the rock is not stopped. Consequently, a larger number of transverse tree trunks is required to stop all rocks and, to increase the number of stopped rocks, the structure height has to be determined in relation to the rock size which promotes, in most cases, structures made of stacked trees.

Keywords: Rock fall, forest, field experiments

INTRODUCTION

Although recognised since centuries, the protective function of forests against rockfall continuously gains importance in densely populated areas and along traffic ways throughout the Alps. Maintenance of these forests, in order to optimise or sustain this protective function, which accounts for all types of protective measures, has become an important task for persons responsible for managing those forests. Common practices in the European Alps show that a considerable part of the trees felled in rockfall (and also avalanche) protection forests are left in place, in oblique position to the steepest slope direction. This is being done to compensate for the temporary loss of protection due to the reduced forest stand density in the felling area. These fellings are, however, necessary to promote natural regeneration of the, in many cases, over-mature protection forests. Although being a widely used technique, there is little objective information on the efficacy of these trees felled transverse to the slope (in German: Querfällung). Therefore, the research work presented in this paper aims at providing practical information to stakeholders, foresters, and natural hazard managers to quantify the protective function of such structures and at defining optimal design schemes (trunk anchorage, optimal oblique stem angle regarding the steepest slope direction, dealing with wood decay). For this purpose, full scale (or real-size) rockfall impact tests on mature trees felled across the slope were carried out and filmed at the study site of Vaujany. This site has been used for full scale rockfall experiments since 2002 by the researchers from Cemagref (French research institute in science and technology for the environment).

EXPERIMENTS

The experimental site (Dorren et al, 2006; Bourrier et al., 2009) is located in the 'Forêt Communale de Vaujany' in France (lat. 45°12', long. 6°3'). The study area covers an Alpine slope ranging from 1200 m to 1400 m above sea level with a mean gradient of 38°. The experimental site is part of a

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slope that is formed by a postglacial talus slope (Fig. 1), downslope from rock faces consisting of the “Granite des Sept Laux”, which belong to the crystalline Belledonne massif. The talus cone mainly consists of rock avalanche, snow avalanche, and rockfall deposits. The study site is approx. 100 m wide and 570 m long (distance between the starting point and the lower forest road, measured along the slope). Between the starting point and the lower forest road, it has the shape of a channel with a maximum depth and width of 2 and 10 m, respectively.
The experimental site covers an avalanche couloir and is therefore denuded of trees. However, the trees standing along the border of the avalanche couloir allowed selecting four trees (2 white firs, 1 beech and 1 spruce tree) for the installation of a protective structure using felled trees. They were located around 40m down slope from the release point of the rocks. The four trees were felled by experienced lumberjack from Vorarlberg (Austria) and placed in an oblique way regarding the direction of the couloirs (Fig. 1). Finally, the felled stems were attached to their stumps by wire cables.
Before each single rockfall experiment, the rock to be thrown was weighed by an excavator using a load cell. Its dimensions were estimated by measuring the height, width and depth along the three most dominant rock axes. A total of 50 rocks were released individually, one after the other. The mean volume of the sample rocks was 1m^3.

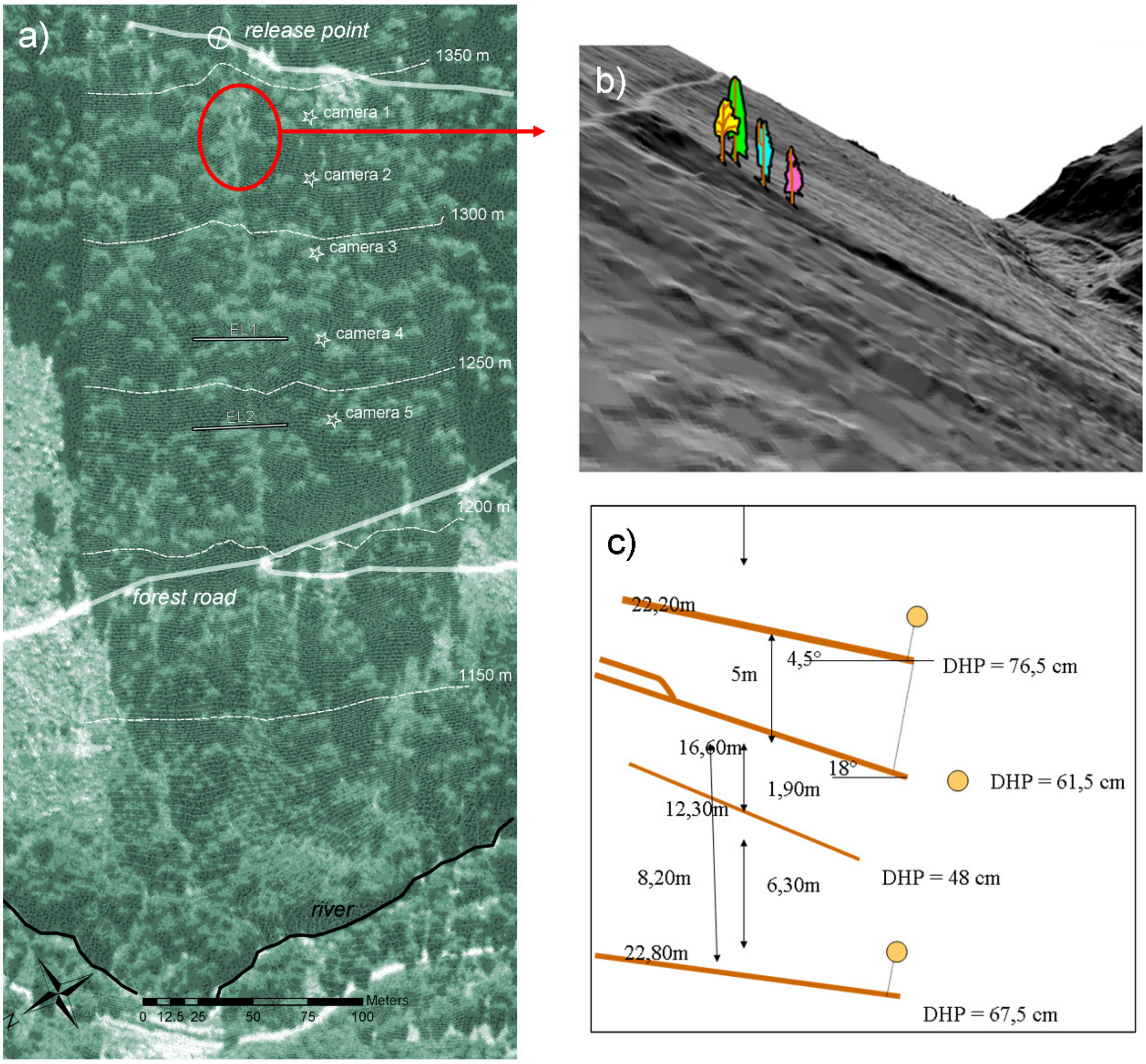

Fig. 1 a) Overview of the study site ; b) Location of the felled tree ; c) Felled tree structure

High-speed cameras (211fps) were used to measure the translational and rotational velocities of the rocks before and after impacting the trees felled across the slope. These measures allowed us evaluating the local efficacy of the protective structure in terms of energy dissipation and changes in fall directions. The velocities and passing heights of the rocks were also measured at two "evaluation lines" located 185 and 235m from the release point using two video cameras. These measurements were done to be compared with similar values without protection structures measured at the same evaluation screens during the experiments described in Dorren et al. (2006). This comparison allowed evaluating the global efficacy of the installed protective structure.

Analysis of the digital footage was carried out to determine the trajectories of the rocks before and after impact on the felled trees. For a given impact, the measurement of the trajectory just before an impact gives the incident translational and rotational velocities. Reflected velocities were obtained by analyzing the trajectory after impact. It was not possible to measure all six velocity components in three dimensions using the cameras. The cameras can only be used to measure the projection of the translational velocities in the camera frame and the component of rotational velocity around an axis perpendicular to the camera frame. However, projection errors are limited in this context because the rocks are travelling approximately parallel with the plane of the camera frame and rotating in this plane.
Frame images were extracted from the films using an image interlocking suppression process for every 1/211th second for cameras in the neighbourhood of the felled trees and for every 1/50th second for the camera at evaluation lines. Processing of every image allowed determining the contour of the rock and, as a result, calculating the location of the gravity centre of the rock and the orientation of the rock in the image. These data had to be converted from pixel units to metric units. The conversion ratio is calculated for each image from the measurement of the distance in pixels between specific points whose distances were measured in the field. For each impact, different point couples were used to estimate the error included in the conversion factor.

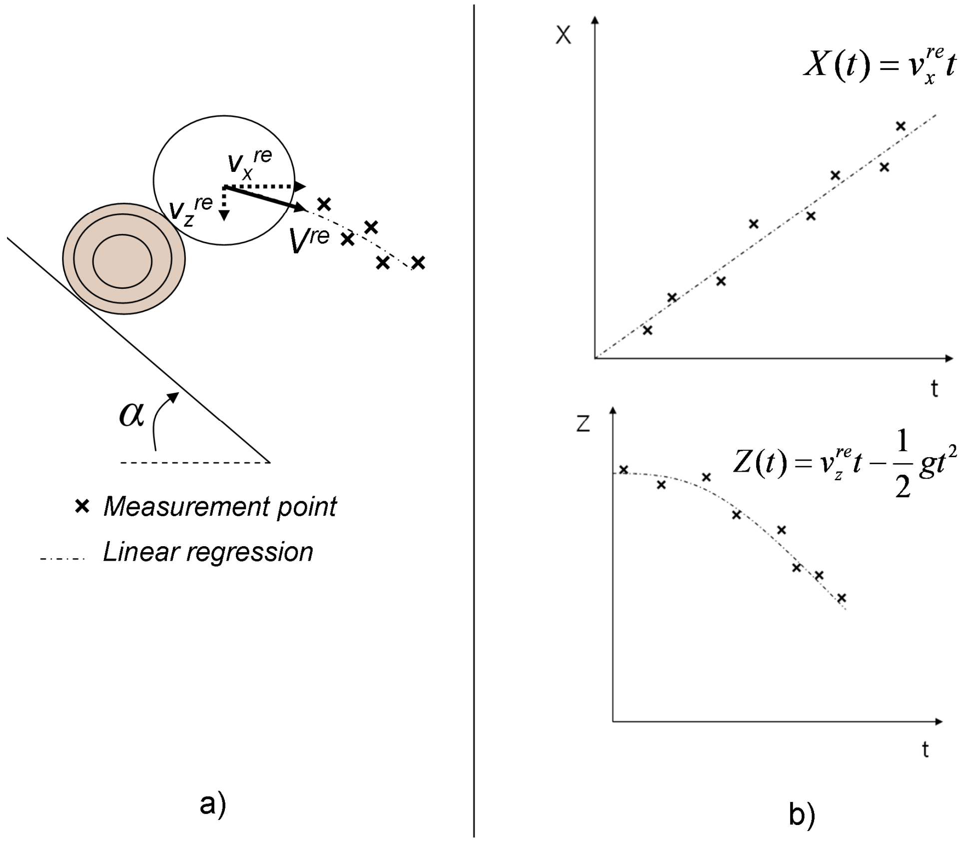

Fig. 2 a) Principle of the analysis of the measurement points using linear regressions to obtain the values of the reflected velocities ; b) Linear regressions for the derivation of translational velocity components

The reflected and incident velocities were calculated from linear regressions of the time evolutions of the location of the gravity centre of the rock and of its orientation (Fig. 2). The regression relationships are based on the theoretical equations of the horizontal and vertical motions of a rock under gravity, for free flight phases between impacts (ballistic trajectory). Linear regression of the time evolution of the particle orientation also allowed calculating the mean rotational velocities of the rock before and after rebound. The calculation process is illustrated above for reflected velocities.
The error on the measured velocities can be decomposed into the error in the value of the conversion factor from pixel to metric unit and the rock gravity centre identification error resulting in the regression error. The errors were quantified by indirect methods to estimate the accuracy of the velocity measurements. The conversion factor was calculated for one image using 10 different known field point couples. The maximum difference in the calculation of the conversion factor is 6.3% of the minimum values of the factor. To estimate both the regression error and the error on the rock gravity centre identification, the same film was treated 10 times. From these 10 measurements, the mean regression residual is of the order of 0,05 m and the maximum difference between the norm of the velocities is 9,1% of the maximum velocity obtained.
For the velocities after impact, called reflected velocities, the theoretical trajectory of the rock gravity centre just after rebound is characterized by the equations (Fig. 2b):

$$X(t) = v_x^{re} t \quad (1)$$

$$Z(t) = v_z^{re} t - \frac{1}{2} g t^2 \quad (2)$$

where X(t) and Z(t) are the horizontal and vertical positions of the rock gravity centre, v_x^{re} and v_z^{re} are the horizontal and vertical components of the reflected velocities, g is the gravitational acceleration, and t is the time starting from the end of the previous impact on the soil.

The components of the rock velocity tangential (V_t^{re}) and normal (V_n^{re}) to the slope surface are calculated from the horizontal and vertical components:

$$V_t^{re} = v_x^{re} \cos\alpha - v_z^{re} \sin\alpha \quad (3)$$

$$V_n^{re} = v_x^{re} \sin\alpha + v_z^{re} \cos\alpha \quad (4)$$

where α is the mean slope angle in the vicinity of the current rock position (Fig. 3a).

RESULTS

The experiments (Fig. 3) at first show that 85.7 % of the released rocks impacted the structure and only 8.5% were directly stopped. 14% of the rocks impacted 3 felled trees, 31% impacted 2 trees and 40.7% impacted only 1 tree.
The velocities of the rocks before and after rebound (Fig. 4) were decomposed into a normal and tangential (with respect to the surface) components. The relative parts of these components before (called incident velocities V_n^{in} and V_t^{in}) and after (called reflected velocities V_n^{re} and V_t^{re}) impact were measured. Le rotational velocities before (ω^{in}) and after (ω^{re}) impact were also recorded. The rotational velocities were multiplied by the mean radius of the rock R_b and scaled to the value of the translational velocity before impact V^{in} defined as follows:

$$V^{in} = \sqrt{V_t^{in} + V_n^{in}} \quad (5)$$

The tangential and normal velocities were also scaled to the value of the translational velocity before impact V^{in}.

Fig. 3 Snapshot of the impact of a rock on a felled tree

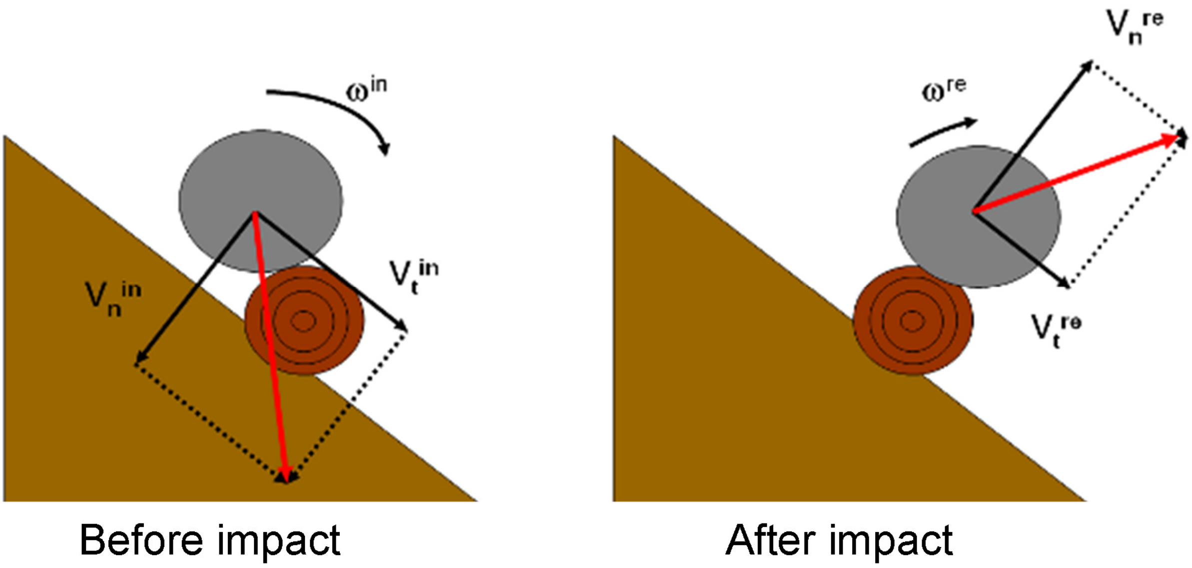

Fig. 4 Tangential and normal velocities before and after impact

Tab. 1 Means and standard deviations of the tangential, normal and rotational velocities before and after impact

	Before impact		After impact		Diff. After/Before
	Mean	Std. dev.	Mean	Std. dev.	Mean
V_t/V^{in}	96 %	4 %	64 %	24 %	-32 %
V_n/V^{in}	23 %	14 %	26 %	14 %	-3 %
$R_b\omega/V^{in}$	0.4 %	0.01 %	0.3 %	0.01 %	-0.1 %

Based on the analysis of 25 rebounds (Tab. 1), the results show that the tangential components of the velocity were significantly reduced (- 30%) whereas both normal and rotational components were hardly modified. The impact on the structure therefore induces kinetic energy losses. Changes in the fall direction towards the direction of the felled stem were also observed.

The passing velocities and heights to the slope surface were measured for 16 rocks at evaluation line 1 (EL1 – 185m from the release point) and 13 at evaluation line 2 (EL2 – 235m from the release point). These measurements allowed estimating the mean and standard deviation of the velocity and passing height distributions that were compared with these values without felled trees. Velocity and passing height without felled trees were measured for 102 rocks during previous experimental campaigns (Dorren et al., 2006). No significant differences with and without the protective structure were observed for the velocities and passing heights at the two evaluation screens located more than 100m further down slope (Tab. 2).

Tab. 2 Comparison between the mean and standard deviation of the rock velocity and passing height with and without felled trees at Evaluation Line 1 located 185m after the rock release point.

	Without felled trees		With felled trees	
	Mean	Std. dev.	Mean	Std. dev.
Velocity (m/s)	12.5	5.2	15.3	4.2
Passing height (m)	1.4	1.1	1.3	0.7

DISCUSSION

Despite significant energy losses when impacting the structure, the rock energy significantly increases again after the structure. Consequently, a larger number of transversely felled trees is required to stop all rocks. In addition, the structure height seems to be not sufficient: in this site and for $1m^3$ rocks, structures made of stacked trees could be significantly more efficient. However, this assumption should be proven by additional experiments. As these structures are much more complicated to establish in steep terrain the efficacy is a major cost factor.

Additional criteria for the design of felled tree structures are therefore required for such structure to be efficient with regards to structure height compared with rock size. One could therefore recommend using structure heights larger than the highest rock size although this recommendation has to be confirmed by additional experiments. In this case, using structures made of piled trees would therefore be more efficient (Fig. 5, Fig. 6).

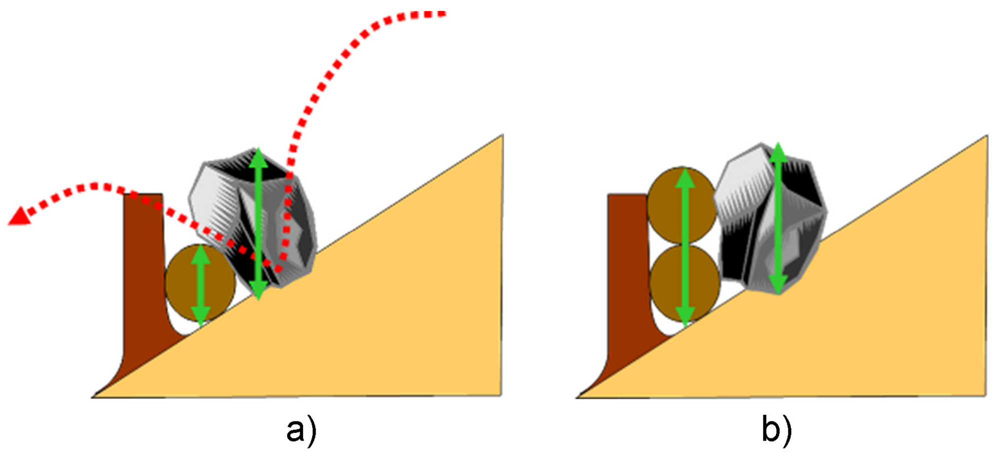

Fig. 5 Examples of felled trees structures designed in an non efficient (a) and efficient (b) way with regards to the structure height compared with the larger rock size

Fig. 6 Example of a structure made of piled felled trees (Cemagref, 2008)

The results also show that the rocks that were not stopped by the felled trees gain velocity again after have passed the structure. This induces that the differences in the passing velocities at the evaluation lines with and without felled trees are smaller than expected. However, a more important mean velocity combined with a smaller standard deviation of the velocity distribution with felled trees tends to show that the rocks passing the structure are associated with large velocity and, consequently, that stopped rocks are associated with small kinetic energy. The structures are therefore, obviously, more efficient for the rocks that have the smaller kinetic energy. One could therefore assume that, in forested slope, where the rocks velocities are smaller (Dorren et al., 2006), using felled trees structures is more efficient due to the combined effect of these structures with standing trees.

The interaction with felled trees also strongly modifies the rocks trajectory. In particular, the mean of the tangential component of the rocks velocity is significantly reduced whereas the mean of the normal component of the velocity is not modified. The free flight of the rock is therefore higher from the slope surface and the flight distance is smaller than if the tree was not impacted. Although further statistical investigations cannot be held given the reduced amount of data, these data provide interesting results concerning the definition of a probabilistic model of the interaction with felled in rockfall simulation codes. Indeed, such a model should consider at least significant changes in the tangential component of the rock velocity.

The changes in the rock kinematic due to the interaction with the felled trees also highlights a potential negative effect of felled tree structures that was not expected. Indeed, the significant decrease of the tangential component shows that the structure may act as a springboard. Such a phenomenon may therefore induce catastrophic consequence if the felled trees are placed near from rockfall nets, for example. However, if design criteria for the structure high compared with the rock size are fulfilled, the structure will stop the rock and the negative «springboard effect » would be reduced.

CONCLUSION-PERSPECTIVES

The experiments allowed testing the efficacy of a protective structure made with trees felled across the slope. The results confirm the empirical knowledge regarding the design of these structures: trees felled in an oblique way have a high probability to be impacted by falling rocks and such trees induce rockfall energy dissipation and a change in the fall direction. On the basis of the field observations, design recommendation regarding the structure height in relation to the mean diameter of the falling rocks has been found. The improvement of our knowledge on these structures however requires further laboratory studies to explore several design schemes as well as additional field experiments to evaluate the efficacy of such structures. These experimental researches should focus on studying the efficiency of these structures in combination with construction costs.

In order to improve our knowledge on the efficiency and on the dissipative capacity of these structures, further experiments are envisaged. In particular, the combined effect of felled tree structure with forest will be studied from similar experiments in a forested slope. In addition, laboratory experiments are currently in progress to provide preliminary results concerning the optimal distance between two felled trees structures, the orientation of the trees relative to the slope aspect…Finally, the dissipative capacity of these structures and its evolution in relation with the aging of the structure will be studied using controlled laboratory impact experiments using a pendulum testing device.

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