FOREST: A NATURAL MEANS OF PROTECTION AGAINST ROCKFALL, BUT HOW TO REACH SUSTAINABLE MITIGATION?

ADVANTAGES AND LIMITATIONS OF COMBINING ROCKFALL MODELS TAKING THE FOREST INTO ACCOUNT

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ABSTRACT

Forests are multi-functional ecosystems, but a major function is not well taken into account: the protective function against rockfall hazards. Therefore, research institutes (dealing with mountain forest management and risk assessment) and a private company (working in the field of risk prevention) are completing a research project on this topic: the ROCKFOR project (http://rockfor.grenoble.cemagref.fr/). The main aims of this 3-year project are: firstly, to incorporate tree mechanical behaviour in a spatial rockfall model in order to assess the efficiency of forest stands against rockfall and secondly, to produce management guidelines for sustainable rockfall hazard mitigation by mountain forests. The "forest-rockfall-trajectory-model" is being calibrated with data obtained from real size experiments and will be used to realize virtual experiments. These experiments allow us to come up with a ranking scale for indices that indicate the capability of forest stands to mitigate rockfall hazards.

This article presents the framework used for realising the virtual experiments and it explains the advantages and limitations of such an integrated modelling tool both for researchers and practitioners.

KEYWORDS: rockfall, risk prevention, forest management, sustainable management, virtual experiments, modelling, tree mechanical behaviour, up scaling, Geographic Information System

INTRODUCTION

The role of mountain forests in protecting against rockfall

Rockfall is a natural phenomenon in mountain areas, which could pose a serious risk both to people, their belongings and the infrastructure. The ability of mountain forests to act as a

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barrier against falling rocks is indicated by the number of injured trees due to rockfall. Nevertheless, it is difficult to determine, let alone to quantify the effect of a forest stand on the rockfall hazard. In our research we define that rockfall as a mass movement of an individual rock in the order of a m^3. Rock avalanches or bigger events are not considered. Knowledge of the protective role of a forest against rockfall would allow us to optimise the management of these forests to increase its protective function and to take them into account during assessments of different protection means against natural hazards. At present, the management of these forests is based on empirical knowledge (Rey et al., 2003). In fact, forest management with respect to rockfall often assumes the following: the more trees, the more impacts against trees; the bigger the tree diameter, the better a tree stops a falling rock. But if these phrases would be true, it would imply worshipping the “big tree”, but this is often incompatible with the environmental conditions on a rockfall slope. Moreover, silviculture aiming at trees with a large diameter does not sustain the protective function of the forest in the long-term. In fact, big trees favour uniform structures and large scale cuttings for regeneration. For a sound protection forest, Bartolli (1998) recommends irregular forest stands that have a large number of juvenile trees and a permanent mature stock. If, however, an irregular structure sustains protection better, the forest administrator still has to deal with questions such as: how effective is the protection provided by the different forest stands; which forest stands are well adapted to a given situation; which silvicultural interventions have to be carried out in the protection forest stands, which tree species, tree density and tree diameters are favourable? In summary, the forest administrator requires specific data on the protective role of forest stands against rockfall. We believe that the use of various models could provide these data and they could help to increase the current knowledge of mountain forests protecting against rockfall.

Characterising existing rockfall trajectory models

The majority of the rockfall trajectory models have been developed since 1985. Most often these models simulate rockfall on a two-dimensional slope profile, in order to assess the effect of different protection means at a given location on the slope profile. These are in most cases technical constructions. Guzetti et al. (2002) stress that rockfall simulation along a slope profile does not allow taking the effects of the topography, e.g. lateral movements, or the effect of vegetation on the falling rock into account. In some models the effect of vegetation is taken into account by adding a bias to the coefficients of surface friction. To determine a kind of a friction value for trees, experiments have been carried out to determine the amount of energy that is dissipated during a rock impact against a tree. These experiences were executed on wood samples in the laboratory, but Roofer (1982) and Doche (1997) showed that the coefficients obtained from the laboratory test underestimated the energy-dissipative capacity of a tree by a factor hundred. Effectively, the root actions and reactions of the treetop to rock impacts were completely neglected during the laboratory tests. Another disadvantage of existing rockfall models is that these models are calibrated using biased data obtained from historic events. Even if data such as the distance between two rebounds of the falling rock, the stopping zone or the starting zone of the falling rock, could be measured, it is impossible to derive the kinematics from these. This introduces an error that is hard to link to reality.

Having identified these gaps in the currently existing models and in order to fulfil the current requirements of foresters, Cemagref developed a method to characterize the protective function of a forest stand based on a combination of a three-dimensional simulation of the trajectory of a falling rock, with a model for the mechanical behaviour of a tree after a rock impact.

A methodology based on combining new models

As foresters working in the field of forest management and silviculture generally think on a forest stand scale, we took the problem in the opposite direction. We started to work on the scale of a single tree to quantify the protection offered at a stand or even a slope scale. Regarding rockfall, foresters use the concept of residual risk, which is characterised by the percentage of the number of rocks that fall through a forest stand compared to the number of rocks that enter the stand. To determine this percentage, we looked at all the individual components of a single rockfall event at the scale of a single tree. These components are: the trajectory of the rock, the roughness and the elasticity of the ground surface, the forest (number of trees, thickness of trees, tree species and the locations of the trees) and models of rebounds on the ground and against trees. Our study aims at validating the combination of these components to carry out accurate and realistic virtual rockfall experiments in forest stands. Within this framework a forest stand is not regarded as a whole, but as a collection of "tree elements". In this paper we will describe which tools we use and how we link them. Further, we will evaluate the consistency of this linkage and we will present the obtained results, as well as the foreseen improvements.

METHODS AND SOME RESULTS

Modelling the mechanical behaviour of a tree during a rock impact

A tree is a living organism and is therefore a complex system. This complexity stems from the macroscopic and microscopic elements (both chemical and physical), their organization and the functional relation between them. During the impact, this complexity expresses itself in the response of the tree as a whole. After onsite observations, we describe the impact of a rock on a tree into two distinct phases. The first phase is the impact, the contact between the rock and the tree. The second phase is the consequences of the impact, the propagation of the mechanical stimulus caused by the impact, which could lead to damage to the tree.

The main hypothesis for modelling the mechanical behaviour of an impacted tree is that the two phases overlap. Taking into account the different spatial and temporal scales, a specific model must be developed for each phase (Fig. 1). The first phase models the local scale with a temporal scale of about one-tenth of a second (only the moment of contact). The impact force, the local damage and the rock velocity will be determined. The rock velocity is also part of the trajectory model. The second phase models the global scale with a temporal scale of a few minutes. Three main types of tree damage will be assessed: uprooting of the tree, breakage of the foot or the top of the tree, or less damage then the previous ones. The tree will be spatially represented on two scales.

Firstly, the local scale, for which the analysis uses the balance of linear momentum. The displacement of the rock and the induced impact force are obtained step by step. To model the cohesion matrix between the fibres, we use the simple hypothesis that the fibres are a succession of overlapped cylinders with a cohesion force between them.

Secondly, the global scale. The tree system is decomposed into three elements: the root, the trunk and the branches. A non-constant section beam represents the tree, with an elastic kneecap at the foot. The branches are represented as a mass added to the trunk's mass and a viscous force applied at the height of the crown.

The general objective is to determine, for a given impact, the damage to the tree. The principle is to know the stresses at each point of the tree over time and to determine the location of the point where the stress exceeds the breaking limit. For further details on this model we invite the reader to consult Quètel et al. (2003).

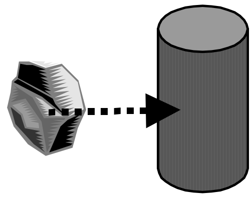
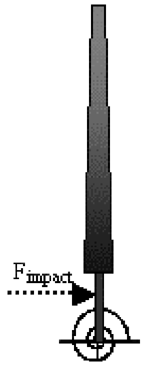
Phase	**Contact**	**Tree behaviour**
Temporal scale **Spatial scale**	During of impact [0.01s] Impact area	During of movement [2s] The tree
Model		
Informations obtained	- rock speeds after impact, - local damage of the tree, - form of the impact force.	Global damage: - tree uprooted, - tree broken on the top or the foot, - less damage …

Fig.1: Synthesis of the two models for simulating a rock impact on a tree.

3D trajectory model of a falling rock

Dimnet and Fremond (2000) developed a model that calculates the trajectory of a falling rock (*Trajecto*) that simulates a bouncing and falling rock and both the rock and the surface are represented in 3D. The composition of the ground surface is represented by two restitution coefficients. To simulate the bounces or rebounds, the "Percussion Theory" is used (for explanation see Fig. 2). It requires knowing the position of the rock and its velocity before the impact. The velocity after the impact is calculated according to the mechanical law of the behaviour of elements in contact. Figure 2 explains the general operation of calculation.

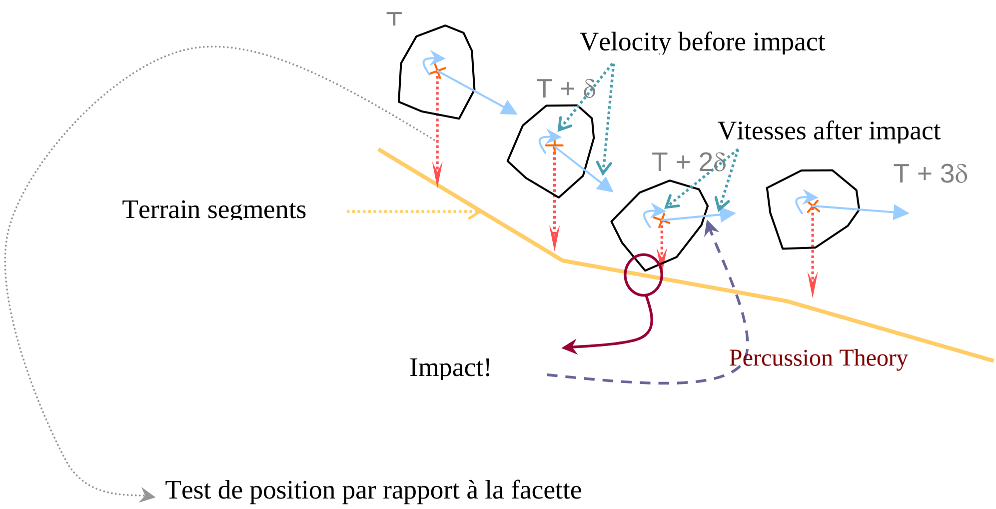


Fig. 2: A scheme explaining the functioning of the software " *Trajecto*".

Combining the models and the use of GIS

As described, the model for calculating the trajectory of the rock uses a three-dimensional representation of the topogrphy. For this we chose an irregular triangulation network, more specific we developed a module that applies Delauney triangulation (Koua, 2001). Delauney triangulation permits to use both regular and irregular grids as input (Fig. 3). A representation by an irregular triangulation network allows a better spatial resolution than a grid with quadrangular cells (Guzzetti et al., 2002). It also allows managing the data that characterise the ground surface more easily. This information is very diverse (land cover, soil type, elasticity, etc...). To represent these data, the values that correspond to the real ground surface, are being assigned to each triangle.

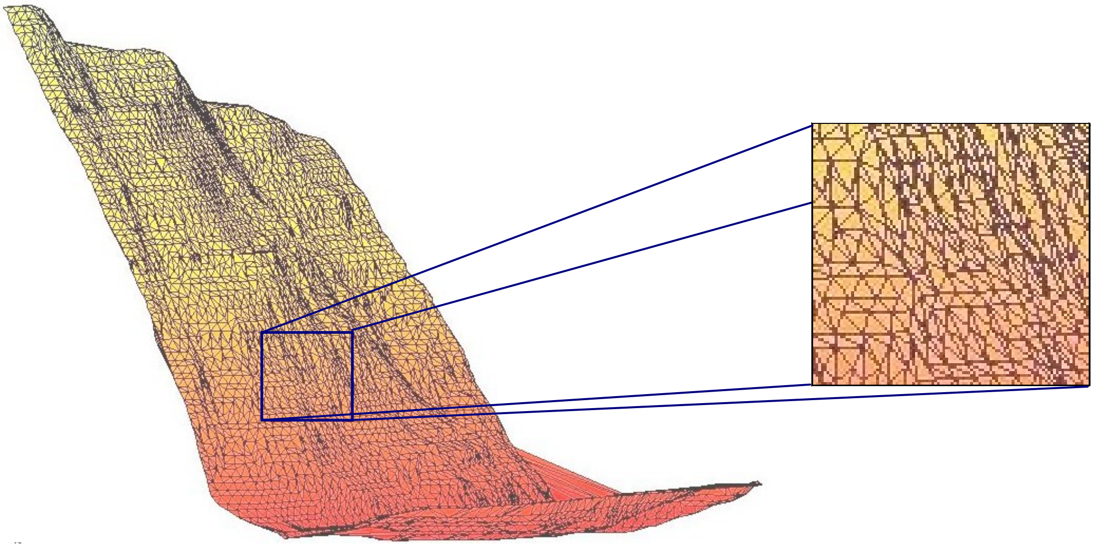


Fig. 3: Example of a terrain three-dimensional representation based on the Delauney triangulation.

At Cemagref, the link between the GIS and the trajectory simulation model is currently being developed to facilitate the exchange of files. During the trajectory simulation of a falling rock, an algorithm calculates which slope elements have been flown to detect the location of the rebound on the ground surface. The condition for a rebound on the ground is that one of the points located on the periphery of the simulated rock has an altitude equal to that of the slope surface that is over flown. The principle of the integration of the trees in the trajectory model has been derived from the one used for the ground surface type representation. As described the trajectory model detects the locations of the rebound and then it calculates the rebound on the appropriate ground element for which the proper mechanical properties are assigned by the GIS component of the model. After that, the first stage is our model development was to physically integrate trees as obstacles on the ground surface. The tree, which has the shape of a pillar, is triangulated with the same principle of triangulation as is used for the ground surface. As a result, the detection of an impact against a tree is similar to the detection of a bounce on the ground surface. If the coordinates of the position of a tree on the ground are known, the tree diameter at its base also has to be known.

The following stage was the characterisation of the mechanical behaviour of the trees in the model. For that we still use the principle implemented for the characterization of the grounds elements, which are assigned by two coefficients. While waiting for accurate parameter settings for the tree mechanical behaviour model, we use the coefficients that are used to characterise the ground surface, in order to test the various developed data-processing modules.

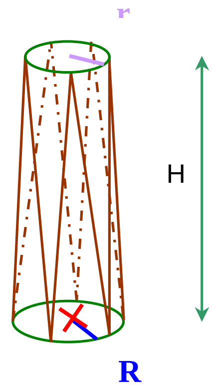


Fig. 4: Triangulated representation of a tree in the trajectory modelling.

Figure 5 explains how the model operates after integration of a "triangulated" tree and Figure 6 presents an exaggerated visual representation of this integration.

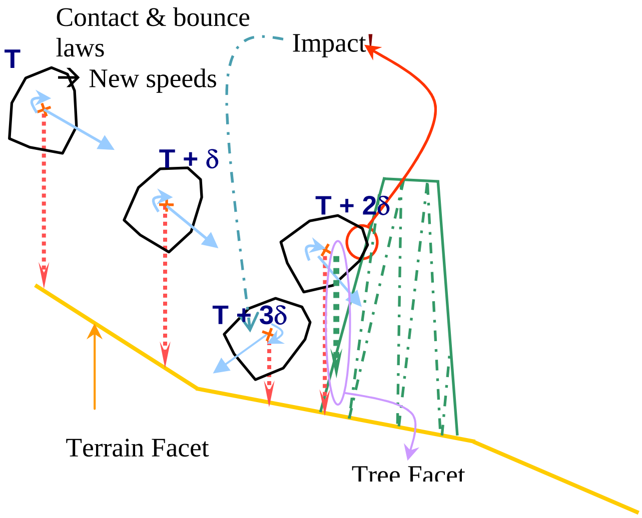


Fig. 5: Model functioning including trees.

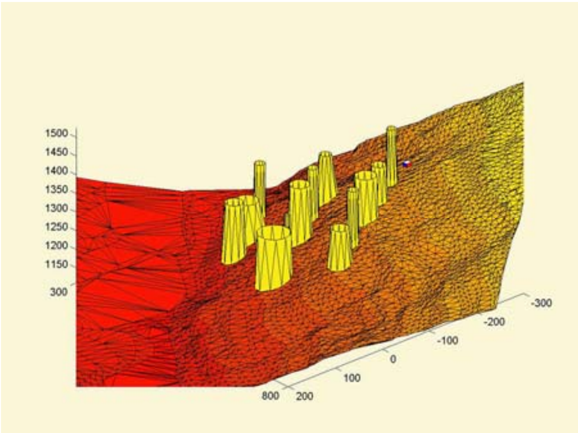


Fig. 6: Integration of trees on the terrain.

Once the ground surface and the trees where integrated in 3D, the model had to be calibrated for the study site. The need for reliable data, in particular for data on the kinematics, resulted in the development of a plan to carry out real-size rockfall experiments in a mountain forest.

Acquiring trustworthy data: real-size experiments

The data required for calibrating the developed models are mainly obtained from our experimental site in Vaujany (France), on which real-size experiments have been carried out. From a forester point of view, the main objectives of these onsite experiments were threefold. First, to quantify the energy dissipative capacity of a tree and second, to investigate which deviation of the fall direction is caused by an impact on a tree and to assess for a given distance how many impacts against trees are needed to stop a falling rock. To fulfil these objectives it is necessary to capture or measure the position of a rock in any point of its trajectory, both in space and time. With this information it is possible to calculate the velocity (translation and rotational) of a rock in any point of its trajectory and to calculate the direction of the rock (Figure.7).

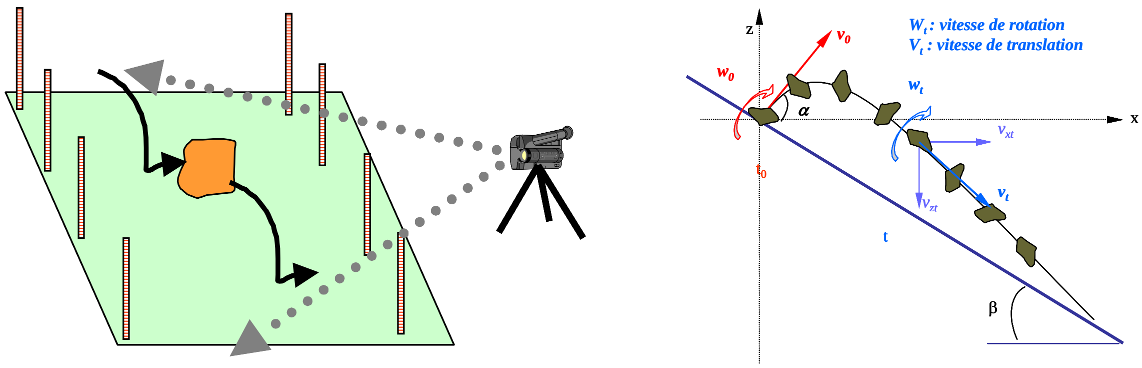


Fig. 7: Schematic representation of the experimental setting and of the measurable data on numerical film between two impacts.

Because of the previously described requirements we use high-speed digital video to track the trajectory of falling rocks. The characteristics of each rock are known, such as the dimensions, composition and mass. In addition, all the terrain characteristics are known and available in maps, such as the digital model of ground surface, the type of soil cover, the position of all the obstacles such as trees, big rocks, etc. The missing information is the exact location of the impacts of the rock. These are precisely mapped with a tachymeter after each rockfall experiment. The experimental site of Vaujany provides the excellent opportunity to carry out rockfall experiments both in a non-forested channel and in a forested sector. Here we stress that the slope topography is identical in both sectors. This allows us to compare the data obtained from these two experimental sites.

On both experimental sites we carried out 100 real-size experiments. The rocks were released one after another. Currently 200 individual rockfall experiments were carried out. These real-size rockfall experiments in a forest are the first ones ever done worldwide. Due to the success of the experiments we decided to carry out another experimental campaign in October 2003. Figure 8 presents the study site in Vaujany in 3D.

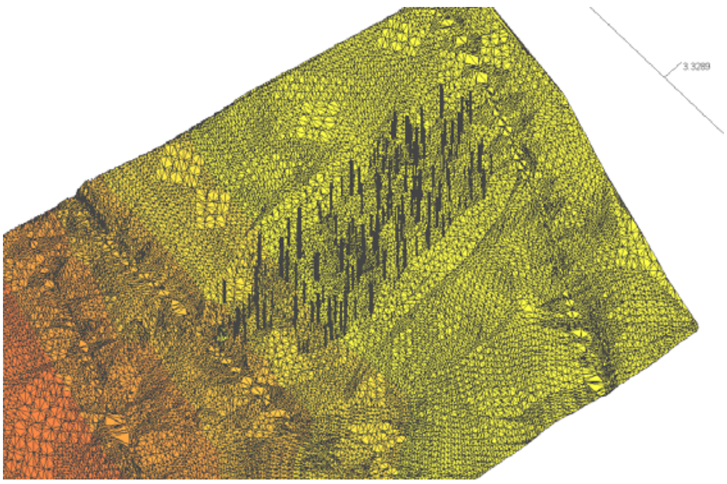


Fig. 8: Three-dimensional representation of the trees and topography of the real size experimental site.

On the whole, 99 impacts on trees could be analysed using obtained video data. For each of these impacts we determined the height of the impact on the tree, the position of the centre of the impact compared to the vertical axis of the tree, the depth of the impact, both the incidence angle and the exit angle of the rock, the azimuth of both the arrival and the exit of the rock, the translation velocity before and after the impact and finally the rotational velocity before and after the impact. This also enabled us to calculate the coefficients of restitution of the ground of the experimental site, because we could calculate the tangential and normal components of the translation velocity before and after a bounce on the ground surface. Some of these data are presented in Table 1 for the non-forested site.

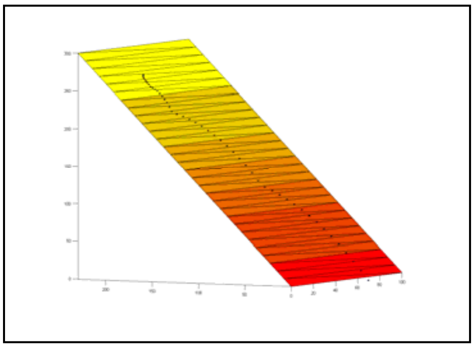
Tab.1: Example of results obtained with the cinematic calculation, tangential and normal components of the soil restitution coefficient for the non-forested experimental site.

	Tangential restitution coefficient	**Normal restitution coefficient**
Mean	0,70	0,26
Maximum	0,95	0,41
Minimum	0,56	0,11
Stand. Dev	0,12	0,09
Nr. of analysed bounces	178	

Planning virtual experiments

On the basis of historic events it is very difficult or even impossible to classify the efficacy of a forest stand to protect against rockfall. In fact, studying historic events restricts us to sample only a few forest stand types. Moreover, the topographic and soil conditions, as well as the size and the starting area of rocks are varying from one site to another. To come up with a hierarchical framework in which forest stands can be compared with others, with respect to the protective function, we need to work with identical topographic and soil conditions. Consequently, to understand the influence of the tree parameters on the propagation of a falling rock, it is necessary to be able to work in an environment that is predetermined by the operator. This environment consists of a given topography, a type of ground surface and a certain rockfall event. Within such an environment, the operator should be able to vary one or more tree/forests parameters, in order to study the consequences of the variation on the propagation of the falling rock. We concluded that this is only possible with virtual simulations. We thus have to develop a set-up for virtual experiments in order to study, for a given tree type, the influence of the following parameters: the tree density, the tree diameter and the spatial distribution of the trees on a falling rock.

In order to free us from topographic variability, we decided to start our simulation work on a tilted plane with the same type of ground surface as is present on our experimental site. Then we calibrated the trajectory model with the data from the onsite experiments in Vaujany and we fixed its parameters. After that, it was in working condition for our virtual ground surface. Initially, we decided to work with a rock of which the characteristics (mass, dimension, initial velocity, starting position and starting orientation) are constant for each simulation. Thus, we varied only the parameters of the forest stand. Figures 9, 10 and 11 present examples of these simulations.



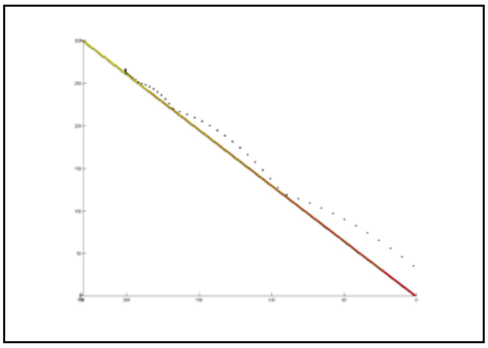
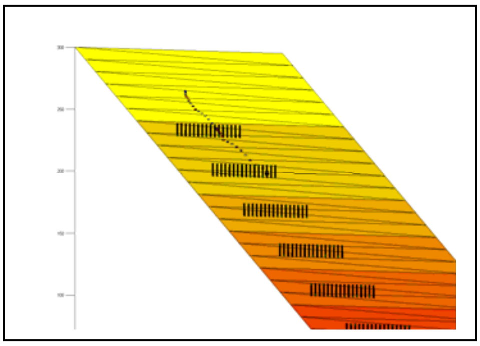


Fig.9: Example of the propagation of a 0,5 m3 rock on a inclined plan without any vegetation.



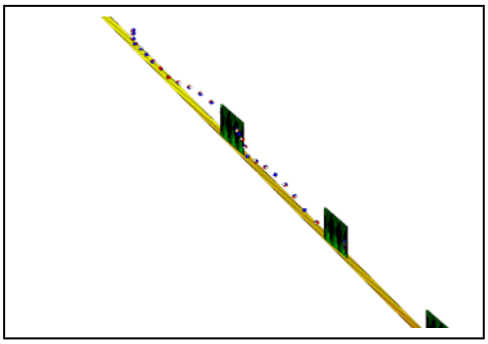


Fig.10: Example of the propagation of a 0,5 m3 rock on a inclined plan with a spatial organization of the trees in curtains.

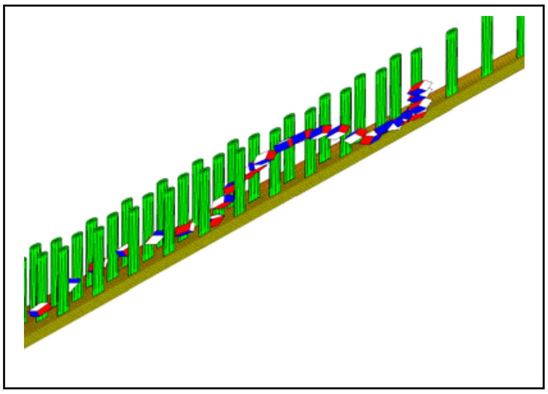


Fig.11: Example of the propagation of a 0,5 m3 rock on a inclined plan with an homogeneous spatial organization of the trees

This experimental design was established in order to obtain information relating to the deviation, the passage heights of rocks, the velocity, and the percentages of rocks that exit the forest stand, for each studied forest stand. It also enables the assessment of the protective function of each forest stand, by comparing the results obtained on a non-forested slope with those obtained on a forested slope. If the whole experimental set-up is completed, data analysis will be carried out in order to develop an index that characterises the protection offered by the investigated forest stands. This index will enable foresters to compare different forest stands with another in reality.

OVERVIEW AND DISCUSSION

Combining the models

In order to reproduce a rockfall through a forest virtually, we chose to develop separate models for the different components of the phenomenon. We developed a 3D trajectory model and a model for the tree mechanical behaviour during a rock impact. Finally we use a GIS platform on which all the spatial data are stored (ground surface data and forest stand data). These models were combined in two steps.

The first step consisted of integrating the triangulated slope surface in the trajectory model. Coefficients that correspond to the type of ground surface in the terrain are assigned to each triangle. The trajectory of the rock is modelled on top of this triangulated surface. The advantage is that the small-scale variations in the relief can be taken into account and that the lateral deviations of the rock can be taken into account. Thus, if a small obstacle, such as a rock outcrop, exists in the micro relief, the passage of the rock at either side could be represented in the model.

The second step consisted of the integration of trees in the model, which is completed recently. To each tree present on the slope a coefficient can be assigned that corresponds to the type of tree. Therefore, the differences in tree mechanical behaviour of the various species are taken into account. The rock can virtually bounce against on these trees and/or be stopped according to the type of impact, the velocity and the type of tree.

All the combined models are currently working and the first virtual experiments can be carried out. In particular, we reproduced (after setting the parameters on the basis of the obtained field data) certain rockfall trajectories observed in Vaujany. Calibrating the coefficients for the tree mechanical behaviour still has to be done. Combining these models enables us to vary forest parameters (position of trees, diameter, height, species), in order to carry out virtual experiments with different stands.

Using GIS

Currently, the use of GIS could be improved. At present, the model combination with the GIS is actually a simple transfer of files and data storage. As stated by Gomez-Fernandez (1999), the majority of the developed applications uses the GIS only to store data, display results and query databases that often originate from other sources, although its possibilities can be useful throughout the whole procedure of risk evaluation. We envisage in the medium term to embed our model completely within a GIS environment. To optimise the use of our developed modelling tool, it proved to be necessary to improve the user-friendliness. It would indeed be interesting to have a dynamic GIS modelling tool in which the starting position of a falling rock, the ground surface cover and the distribution of the trees within a stand could easily be changed.

Meeting the requirements of the forester

To manage forests with a protective function against rockfall in an optimal way, forest managers need information to characterise the efficacy of various forests stands to protect against given rockfall events. Finally, they also need to know the cumulative effect of a mosaic of stands. As a consequence, they are searching for a methodology to make these diagnoses and for a tool that helps them to pass from the scale of the small inventory square to the slope scale. For this reason we briefly presented this modelling tool, which is a first response to the requirements of the forest experts. However, if the conceptual framework is worked out and tested, several stages still have to be realized. The parameter setting and the calibration of the tree mechanical behaviour model have to be finished. Further, we have to complete the virtual experimental design and to synthesise the findings obtained at a tree scale for the forest stand scale.

At present, the combined modelling tool is above all a research tool for carrying out virtual experiments. It is not a very user-friendly tool; computing times are not optimised and interfaces are not very welcoming. In addition, before using this tool, all the trees present on the test site have to be described by the forester, whereas normally only statistical or typological inventories are carried out to describe forest stands. Shrub type vegetation cannot be represented with this tool. But because of these limitations, the tool offers considerable advantages for the researcher, as it permits to compare the protective function of different forest stand under similar conditions. The advantage for the forester is that a thorough assessment can be presented of the capacity of forest stands to stop falling rocks in specific areas, after the research results have been synthesised. But to transfer the combined modelling tool to the forester at this stage is not possible. Therefore, we will aim future work at developing a user-friendly, "aggregated" version, which enables the forester to work on the scale of forest stands as a whole and not with a collection of individual trees.

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