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FOREST: A NATURAL PROTECTION MEAN AGAINST ROCKFALLS, BUT WITH WHICH EFFICIENCY?

THE OBJECTIVES AND METHODOLOGY OF THE ROCKFOR PROJECT

Frédéric Berger[1], Caroline Quetel[2], Luuk K.A. Dorren[3],

ABSTRACT
Forests are multi-functional ecosystems, but a major function is not well taken into account: the protective function against rockfall risks. Its why research institutes (dealing with mountain forest management and risk assessment) and private companies (working in the field of risk prevention) from France, Austria, Spain and Switzerland have decided to initiate a research project on this topic: the ROCKFOR project (http://rockfor.grenoble.cemagref.fr/). The duration of this project is 3 years and the starting date was the first of January 2001. The project aim is to incorporate tree mechanical behaviour in a spatial rockfall model in order to assess the efficiency of forest stands against rockfall and to produce management guidelines for sustainable rockfall hazard mitigation by mountain forests. This article presents the framework used for the tree mechanical behaviour modelling and the rockfall real size experiments methodology. As the data coming from these experiments will be used to realize a rockfalls simulation models benchmarking, we are not yet authorized to publish the data gained during these experiments.

KEYWORDS: rockfalls risk prevention, forest management, sustainable management, real size experiments, modelling

INTRODUCTION

CURRENT STATE-OF-THE-ART

Forests are multi-functional ecosystems, the sustainable management of which being one of the priorities of the United Nation nowadays.

Sustainable management has been defined as the "*answers to the present needs without compromising the future generation's ability to answer to theirs*" [report of the United Nations Commission named "*Our all future*"; and known as the "Brundtland's report", World Commission on Environment and Development – 1987]. Applied to forested areas, this means *" the management and the use of forest lands, by the way and with an intensity such that they maintain their biological diversity, their productivity, their regeneration ability, their vitality and their capacity to satisfy, now and in the future, their ecological, economical an social functions and this at local, national and world level; without injuring other ecosystems*" [H1 resolution, Ministerial Conference on the protection of forests in Europe, Helsinki, 1993].

One of the major natural hazard for which forest plays a significant role is the rockfalls hazard. Rockfalls consist of free falling blocks of different sizes that are detached from a cliff or a steep rock wall. But rockfalls is a generic term; under this vocable we can find different phenomena. We have to do the difference between the fall of individualised elements and a collapsing in mass. The different kind of rockfalls are classified in function of the volume of the mass in movement and the mechanism of propagation [Rochet L.-, 1987] .

[1] Cemagref, Grenoble Regional Centre - 2, rue de la Papeterie, BP 76, F-38402 Saint-Martin-d'Hères cedex, (frederic.berger@cemagref.fr)
[2] Cemagref, Grenoble Regional Centre - 2, rue de la Papeterie, BP 76, F-38402 Saint-Martin-d'Hères cedex (caroline.quetel@cemagref.fr)
[3] Institute for Biodiversity and Ecosystem Dynamics -Physical Geography, Universiteit van Amsterdam Nieuwe Achtergracht 166, 1018WV Amsterdam (l.dorren@science.uva.nl)

So, according to these criteria:

- a rockfall is constituted of elements with a volume less than $5m^3$, there is no interaction between the elements and the mode of the propagation is an independent one (cf. photo 1)
- collapsing in mass and landslide are phenomena for which the volume in movement is more than $5m^3$, there is a strong interaction between the elements in movement and the mode of propagation is not an independent one (fluidisation is possible) (cf. photo 2)

Photo 1 Example of rockfalls

Photo 2 Example of collapsing in mass

The block movement includes mainly bouncing and rolling, and some blocks become fractured during their movement.

The major impairment of the security and dependability of traffic ways is mainly due to the frequent falls of single blocks and stones. Also, forest stands can be most effective in their protective function with these processes. Therefore, the project presented in this article will focus mainly on the fall of single blocks and stones. The collapsing in mass or rockslides (in German "Bergsturz" and "Felssturz, in French "éboulement en masse") will not be considered in this project.

The movement of falling rocks is influenced by the topography as well as slope surface characteristics and on forested slopes also by the structure and the state of the forest. Up to now, there are several models to calculate the rockfall movements along their trajectories on slopes [Okura, Y. et al.., 2000, Dorren, L.K.A., (in press)]. The input parameters of these models are mostly the topography, the elasticity and the surface roughness of the slope surface [Azzoni, A. and Freitas, M.H. de, 1995]. If vegetation cover is taken into account in existing models, its effect is integrated in a coefficient that characterises the surface roughness of the slope [Dorren, L.K.A., (in press)].

It is known that forest can protect against rockfall [Jahn, J., 1988]. It is unknown, however, how to quantify the level of protection mountain forests provide, or how to manage protection forests in a sustainable way [Kräuchi, N. et al., 2000]. This is due to the lack of scientific models or data that can explain the complex interaction between rockfall impacts and dynamics of protection forest stands [Berger, F. and Rey, F., 2001].

Photo 3-4 Against single rocks with a volume less than $5m^3$, the trees can break, …but they can also stop rocks. Why?

Several studies have been carried out concerning the role of protection forests against rockfalls [Doche O., 1997]. However, in these studies, the energy dissipated by a tree in place, in field and in real conditions, has never been precisely calculated. Thus, if general and qualitative data are available, little knowledge exist about rock impacts on a tree or about rebounds in forest.

Effectively, quantitative knowledge on the tree ability to dissipate energy comes essentially from experiments (for example on material resistance) led in laboratories or on woody test bar. That is one reason why it now exists none model about mechanic behaviour of a “tree” system (on the whole: crown + trunk + roots) during a dynamic impact. Moreover, with regard to the results of first experiments carried out in field trees, it appears that coefficients calculated from laboratory experiments under-estimate by 100 the dissipation ability of field trees [Couvreur S., 1982]. This is due to the fact that laboratory experiments are made on woody test bar and so don’t take into account the different possibilities that have a tree to dissipate the energy produce by a projectile. (cf. Fig.1).

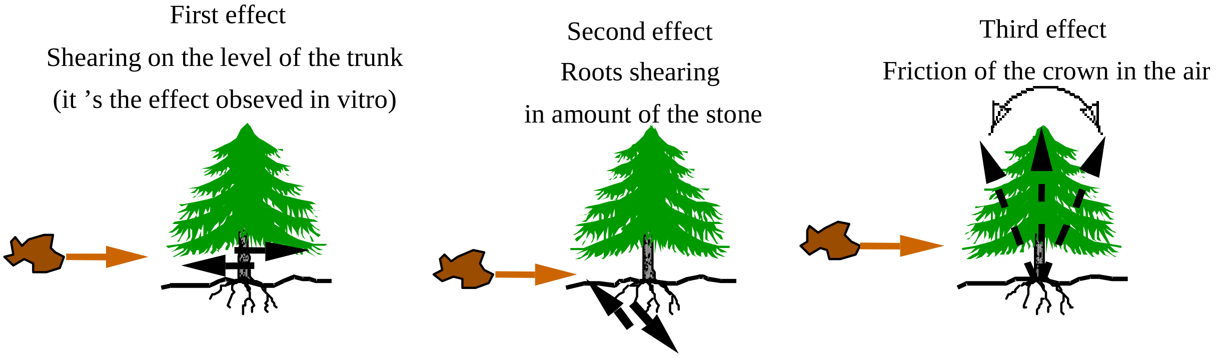


Fig.1 The three effects of a stone dynamic impact on a tree.

This cumulative effect induces methodological problems due to the changes of scale (Cf. Fig. 2). Each scale of investigation corresponds to a specific parameter? Passing from one scale to another one needs to integrate many effects. For example, from the scale of the tree to the scale of the stand, you have to take into account the energy absorption ability of each tree of the stand and their spatial distribution. With these two parameters you can then estimate the maximal mass (called critical mass) that this stand can stop. It's for all these reasons that it’s necessary to investigate each scale. Effectively, having data for each of them it will be then possible for one tree species to find the mathematical law to pass from one scale to another one. But it will be also possible to appreciate, using impact test on wood test-bar, the characteristics of one tree species by comparison with a referential species.

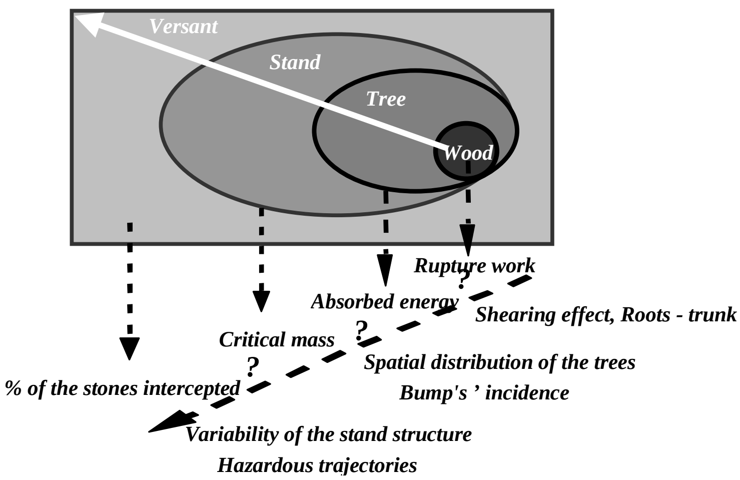


Fig. 2 Cumulative effects and methodological problems of scale changes

But up to now, coefficients obtained in laboratories are those used in the rare trajectory softwares taking into account forest vegetation. Consequently, during trajectory simulations, the role of forest vegetation is under-estimated [Doche O., 1997]. These models are used to evaluate risks and calculate protection work dimensions, necessary to protect people and human equipments. But simulations are only carried out on non-forestes slopes. It is thus necessary to propose a realistic integration of forest vegetation in these models.

Its why, the EU decided to fund ROCKFOR project, which investigates the protective function of mountain forests against rockfall, will provide the required data on the interaction between forest stands and rockfall impacts. However, a systematic and well-structured validation of rockfall simulation models at different scales, which incorporate detailed forest stand data, is still missing.

AN OVERVIEW OF THE ROCKFOR PROJECT

This project aims to help forest managers with defining where and which minimum silvicultural interventions have to be carried out to sustain the protective function of a forest stand. To achieve this, we firstly need to develop a research tool based on a slope scale rockfall simulation model, which incorporates tree mechanical behaviour and which is coupled with a forest growth model. This tool enables us to investigate (by carrying out virtual experiments) where, why, how and for which conditions a forest stand is able to stop falling rocks and which changes occur in time both in a natural and managed forest stand (cf. Fig. 3).

The integration mentioned above first needs the building of a robust model on mechanic behaviour of a tree during the impact with a solid, and second, the use of this model to establish another at the scale of a forest. This second type of model will give information concerning rock stopping probability and, for those completely crossing the forest screen, the energy dissipated during the covered distance within forest. Needed data to establish these models impose to carry out real size experiments?

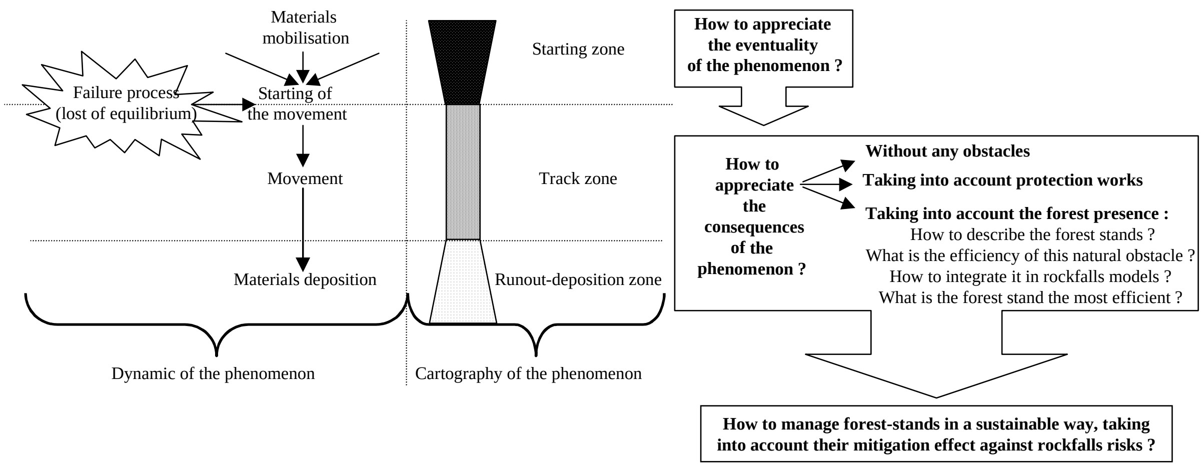
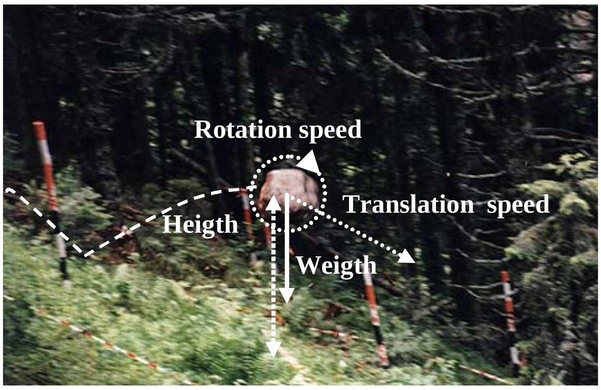


Fig.3 Dynamic phase, mapping of rockfalls and questions to be answered by the ROCKFOR project

In a forest point of view, the main purposes of these field experiments are to quantify the energy that a tree can dissipate and the lateral deviation potentially created by the impact with a tree. To reach these purposes, we must visualize and localize, in a spatial and temporal system of reference, the rock position during its entire trajectory. From this information, it is then possible to calculate translation and rotation velocities developed by a block in all points of its trajectory, and the block direction (trajectory axis) between two impacts (cf. Photo 6 and 7).



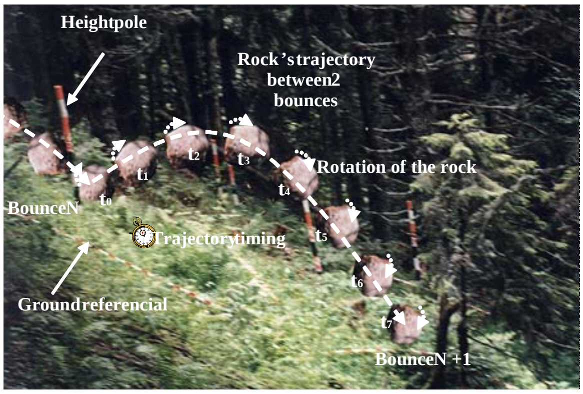


Photo 6 – 7 Data calculable from video film and example of trajectory filmed for a block of 1.5 m^3, on the highest point of this trajectory the instantaneous translation speed is 18m/s

For all these reasons, the ROCKFOR consortium has decided to realize a cinematographic follow-up on trajectories of blocks with precise characteristics (dimensions, nature, weight) in a previously mapped field (digital elevation model, soil use, obstacles position: trees, blocks in place, and so on), and to carry out precise mapping surveys of impacts (position, nature, distance and azimuth between two impacts) after a block pass.

The results allow to structure and establish a database permitting modelling and validation. Moreover, in order to obtain comparison elements, the selected experimental site (Vaujany site, Isère department) allows carrying out, in the same slope conditions, the experiments realized in bare lands and forested lands.

The knowledge obtained will be used to refine the regional scale rockfall model used within the project. Secondly, the developed models have to be transformed into guidelines for sustainable management of forests with a protective function against rockfalls. These guidelines will be formalized in a Strategic Planning Tool, which will be used for rockfall hazard zoning and risk assessment for different forest management scenarios.

To achieve the main objective of this project, five specific tasks have been defined:

- to compare (using well documented past events) the spatial rockfall models used within the project in order to select the most robust ones.
- to implement tree mechanical behaviour model developed by the project consortium in the selected model
- to use this integrated modelling tool to realize virtual experiments in order to assess the effects of different scenarios on the evolution of present protection forest stands and their efficacy in protecting against rockfalls. Scenarios will include a natural situation and situations after different silvicultural interventions.
- to develop and test different methods to scale up from assessment at a forest stand scale (in which individual trees are taken into account) to a management scale (using regional data and forest stand mosaics)
- to use all the results obtained to prepare guidelines for sustainable forest management on active rockfall slopes.

This project is highly original and innovative, since its focus is not at pure defensive techniques against rockfalls hazards but at developing strategies for sustainable protection forest management, taking into account their mitigating effect against rockfalls risks. The most important innovation of this project is that tree mechanical behaviour, rockfall simulation and forest growth models are coupled. This project uses proven state of the art technologies such as dynamic spatial modelling, Geographic Information Systems and decision support techniques. The principal relevancy of this project is that : Forest managers and risk managers require the developed tools and guidelines to improve their management strategies and decisions processes

GENERAL CONCEPTS USED FOR THE TREE MECHANICAL BEHAVIOUR MODELING

In order to design protective structures, we have to predict the trajectory of falling rocks. The rock's trajectory, in a forest, is strongly modified by the different impacts with trees. f some studies was made for determining the tree's energy dissipation ability, there is still no modelling of the mechanical behaviour of a tree to a dynamic solicitation. One of the purpose of the ROCKFOR project consists in modelling this mechanical behaviour of a tree subjected to a rock impact using a multi-scale approach. he general approach of the spherical lump's impact on a tree is:

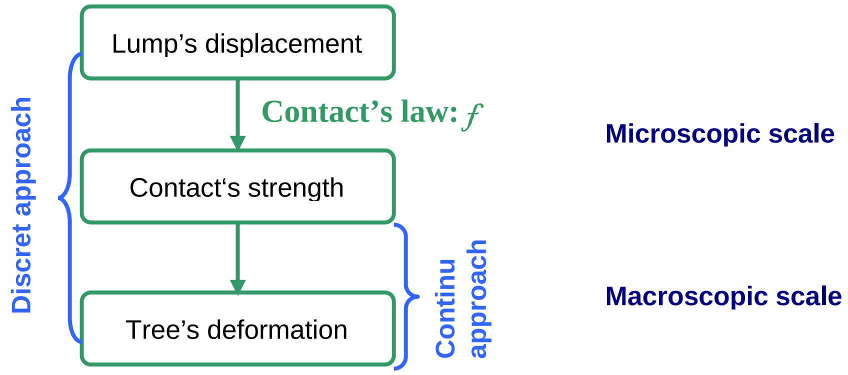


Fig.4 the general approach of the spherical lump's impact on a tree

The parameters we have to determine are: the behaviour's law and breaking's criterion of the trunk, the contact's law and the mechanisms of interaction between soil and structure (root's system).

Initially, the dynamical behaviour of a non-constant section beam is analysed. This beam is loaded by a given time-dependant distribution of pressure. This large-scale model uses the Finite Element Method.

The first step is to model the trunk by a constant and non-constant section beam. Then this modelling beam is discretized for determining the response, the moment and detect the breaking point in the beam. For this, the displacement of the middle fibre is studied. The beam is discretized on one-dimension beam's elements with 2 knots. There is 2 degrees of liberty by knot: displacement and rotation. The study of the middle fibre's displacement is $EI\frac{d^2w}{dx^2} = M$, E is the Young modulus and I the moment of inertia. The solution looking for is $v(x,t) = v(x).q(t)$ and $v(x) = \sum_{i=1}^{n} \vec{v_i}.\overrightarrow{\varphi_i(x)}$.

$\overrightarrow{\varphi_i(x)}$ is the vector of interpolations' functions, $\vec{v}$ the vector of displacements on the element i and n is the number of elements. The function used for representing the displacement of the middle fibre is a polynomial of degree 3. The matrixes of the system: *M*, the element mass matrix and *K*, the element stiffness matrix are obtained by the operations: $M = \int_0^h m(x)\overrightarrow{\varphi(x)}\,\overrightarrow{\varphi(x)}^T dx$ and $K = \int_0^h I(x)\overrightarrow{B(x)}E\overrightarrow{B(x)}^T dx$ with $\overrightarrow{B(x)} = y\frac{d^2\overrightarrow{\varphi(x)}}{dx^2}$ and h the height of an element. The problem we have to solve is $M\ddot{v} + C\dot{v} + Kv = F$. The frequencies are obtained by the operation $\det(M - \omega^2 M) = 0$ and damping coefficients are defined by the relation $2\omega\xi = C / M$. The parameter *C* is not available from the literature, so it will be determined with the real size experiments.

The solution for a distribution of pressure is $v(x,t)=\sum_{j=1}^{\infty} v_j(x)\int_0^t F(\tau)h_j(t-\tau)d\tau\int_D v_j(u)du$, D represents the field x, j the eigenfunction and $h_j(t)$ the function representing the displacement for a distribution of pressure like an unit impulse.

The expression of h is $h_j(t)=\frac{1}{M\omega_j\sqrt{1-\xi_j^{\,2}}}e^{-\xi_j\omega_j t}\sin\left(\omega_j t\sqrt{1-\xi_j^{\,2}}\right)$, $\omega_j^{\,2}=K_j/M$ and $2\omega_j\xi_j=c/M$.

In this part, the trunk is embedded, but in reality the mechanical behaviour at the stem isn't embedded. So we considerate that there is an angular spring with a parameter k defined with the static experiences.

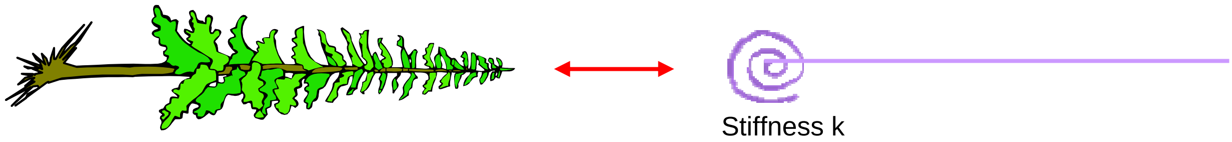


Fig. 5 The concept to take into account the root system

A supplementary degree of liberty at the stem introduces a new equation in the problem: $-Ev''(0,t)I(0)=kv'(0,t)$. This equation modifies the stiffness matrix *K*. In this model, there isn't the action of the branches. So, with the information coming from in situ measurements and relation between the mass of the trunk and branches coming from the literature a model of the branches is introduced in the dynamic model.

The second step is to work on the time-dependant distribution of pressure. This distribution is computed at each time-step by modelling the impact at a local scale. This analysis takes both penetration and sliding of the block into account, by using a Discrete Element Method at the wood fibres scale (Cf. Fig. 6)

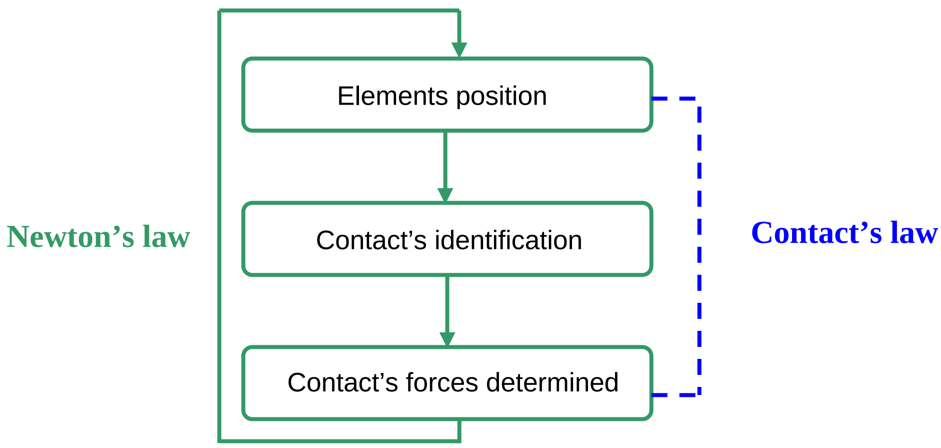


Fig.6 the general algorithm for the Discerte Element method

The hypotheses are the lump levels locally the trunk during the penetration, the contact's plane stays parallel to the initial plane and his parameter is α. The Newton's relations are used for determined the contact's strains *T*, *N* and T_z.

At present, the insertion of the distinct element method in the equations system is under construction. After this, it will be necessary to elaborate the relation between the information coming from the contact and the program of dynamic behaviour.

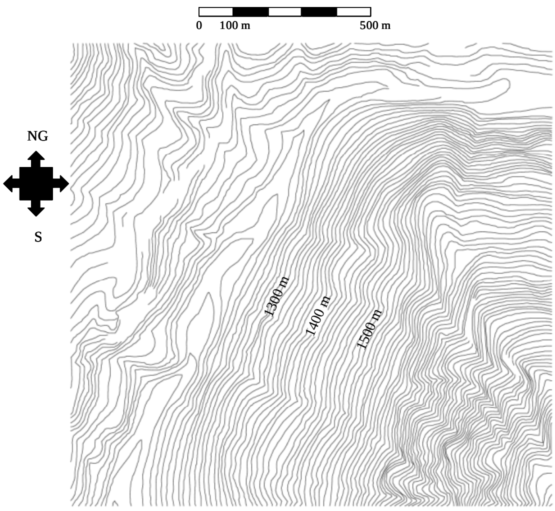
ROCKFALLS REAL SIZE EXPERIMENTS

REAL SIZE EXPERIMENTS METHODOLOGY AND THE CHOICE OF AN EXPERIMENTAL SITE

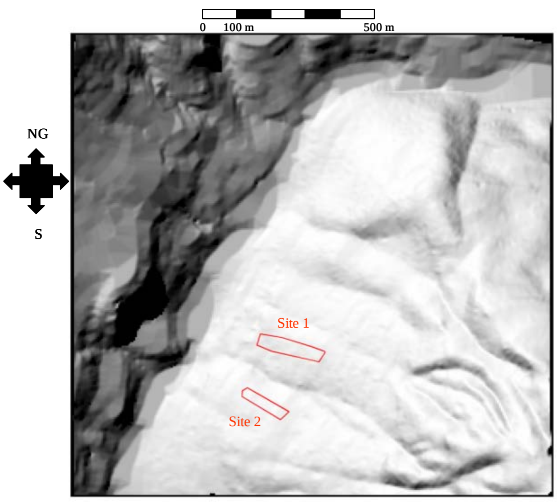
One of the tasks of the ROCKFOR project is to model the action of trees and forest stands on rockfalls' propagation. To reach this objective the consortium needs to have data explaining the dynamic behaviour of trees during an impact by a tree. The method chosen to gather these data is to realize impact tests on trees in situ. The global methodology of these tests is: One block of $1m^3$ is dropped from 5 meters high (using a motorized crane) in the slope and its trajectory is filmed with high-speed numerical video cameras. An infra-red system is used to switch on all the cameras at the same time in order to have the same time code on each films. The CEMAGREF has yet tested (with 15 blocks) the possibility to realise such film and the way to analyse them using remote sensing technologies. Effectively all the data need to calculate the energy developed by a block in each point of its trajectory are available (cf. photo 6 and 7 above). The objective is to film blocks impacts on trees and then to calculate from the film the energy of a block before and after an impact.

An experimental site has been chosen in the northern Alps: site of VAUJANY. The experimental site has 300 m long, 500 m large (including the safety area around the propagation zone), the average slope is 40°, without trees on the first 40 m, which is the distance necessary for a block of $1m^3$ to reach is maximal speed [Gsteiger P. – 1993]. The forest stand presents on the site is composed of spruce, fir, maple and beech trees. Up to now the complete field inventory (position of all the trees, etc.) of the experimental site has been made and implemented in a GIS platform. A Digital elevation Model at the step of 5m has been made. A second digital elevation model, covering the entire valley and based on the use of aerial photos and photogrammetric restitution, is up to now under construction.

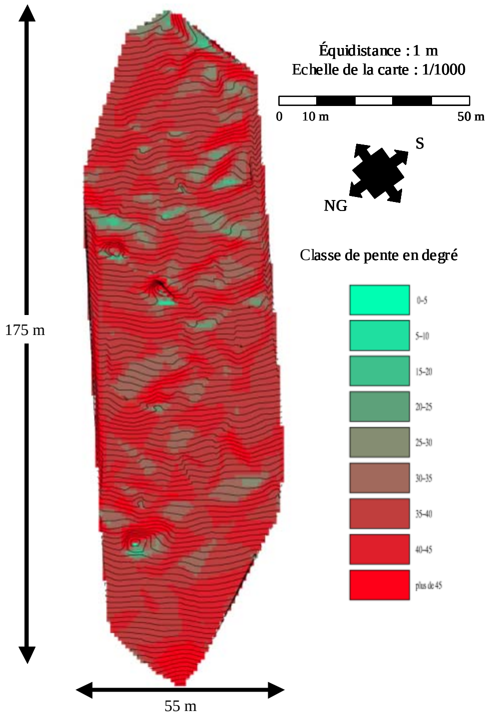
But if we need data to characterize the behaviour of a tree during a dynamic impact, we need also data to appreciate the global action of a forest stand. It's mean that reference data for the same slope condition but for a non forested site are need for comparison. We had the luck to find one site for which all these conditions where present (site 1 : without forest vegetation, site 2 : the forested site). The experimental site has been also chosen in order to guarantee the safety of the operators and there is none stakes in this area. An experimental protocol has been established to forbid the experimental zone to the public and to rule the experimentation development, but also to let the site safe after the experiments phase.The following maps present some of the data gathered during the initial field inventory.



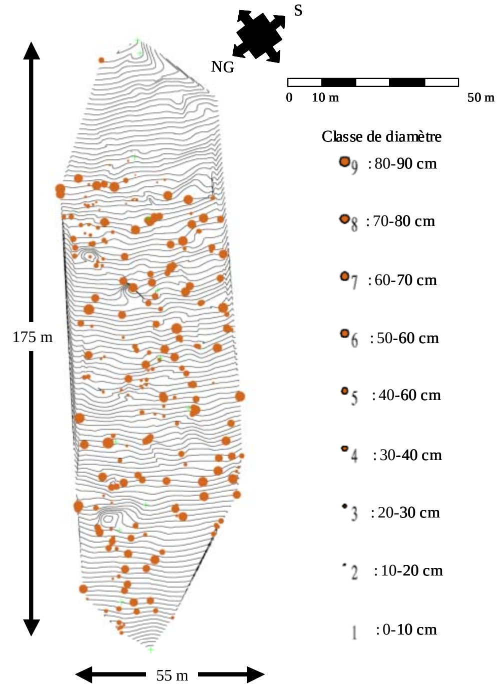
Map 1 Contourlines used for the DEM



Map 2 The DEM of the global sector



Map 3 Slope map for the "forested" experimental site



Map 4 map of the position of each tree

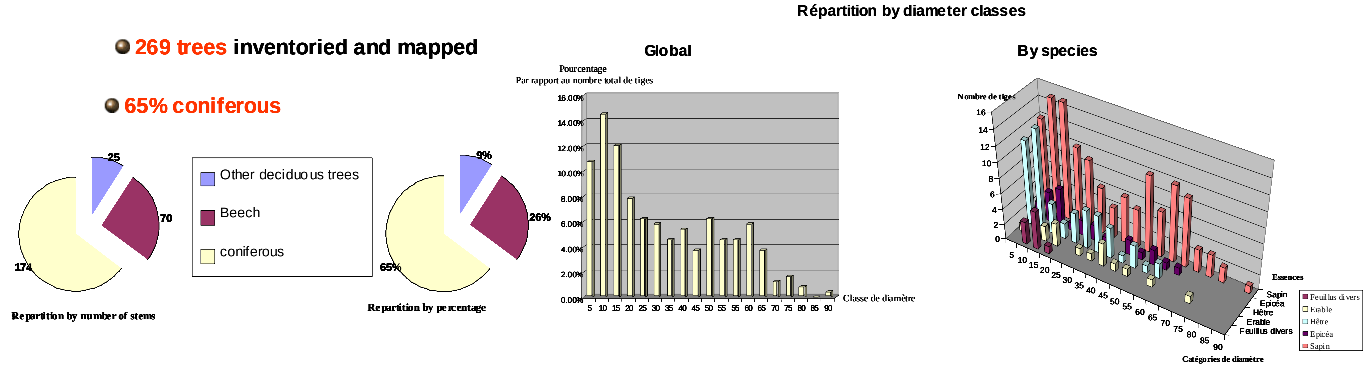


Fig 7 Some results of the forest field survey

FIRST SERIAL OF IN SITU ROCKFALLS REAL SIZE EXPERIMENTS FOR THE NAKED FIELD CONDITIONS

To have a statistical approach, it was provided to use 100 blocks. In fact 33 blocks are enough to have satisfying statistical information. It appears during the experiment that after 50 runs it was impossible to realize the topographic survey of the rebounds in good conditions (quality of the data, safety of the personnel). So we have decided to use only 50 blocks in order to have data with good quality and statistical valuable. The blocks have been dropped one after the other. After each block, a field survey of the trajectory has been made. It has also been verified that the block was in a stable position, if not it was pushed until it finds a stable one. Then another block was dropped, and so on.
The data coming from the field surveys have been implemented in a GIS (Arc-info). The following photography show the main phases of these experiments.

Photo 8 Localization of the experimental site n°1

Five numerical video cameras have been put along the experimental site. They have been installed at 10m high in specific trees situated at 30 m away from the rockfall path. To facilitate the climbing of these trees, wood steps have been fixed on the trunk and a static rope for climbing self assurances was installed.

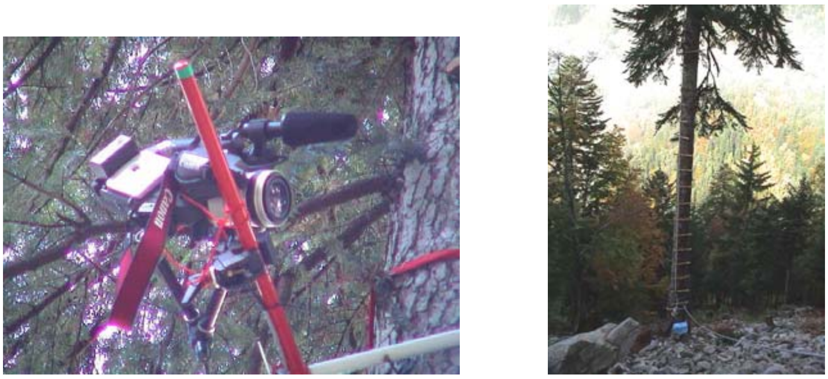


Photo 9 –10 Type of camera used and support platform in a tree

Photo 11 -12 Rocks' preparation and the crane: bio-degradable coloured powder have been used to identified each rock on the numerical films and the rebounds let by he rocks on the ground.

Photo 13-14 A falling rock and Impact survey in the path

DATA GATHERING FROM THE NUMERICAL VIDEOGRAPHIC FILM

Three parameters are calculated from the numerical videographic films. These parameters have to be determined for each rock position on the films. They are : the passing high, the translationnel speed and the rotational one.

The CEMAGREF has developed the methodology to be used for this calculation. For each rock used, the principle of this methodology is:

- To concatenate all the picture of the films in one picture.
- The numerical cameras take a picture each 1/25 second, so on the global picture a rock position is corresponding to 1/25 second. Knowing this value it’s easy to determine the time spend by a rock between two impacts on the soil.
- To use the trajectories topographic survey to calculate the distance between two rebounds. Coupling this distance value with the time ones, the translationnel speed is calculated.
- To calculate the rotational speed from the position following of specific point on the elementary pictures of the rock in the global picture and the coupling with the number of pictures necessary to obtain the same specific position orientation on the global picture.
- Knowing the real size of the rock and the size on the picture, to calculate the passing high using the ratio between these two dimensions.

The calculation phase is still carrying out but we can give for the 50 rocks the average value of the instantaneous maximal translationnel speed: 22 m/s (79.2 km/h). This value is reached after a path of 50m +- 10m along the slope.

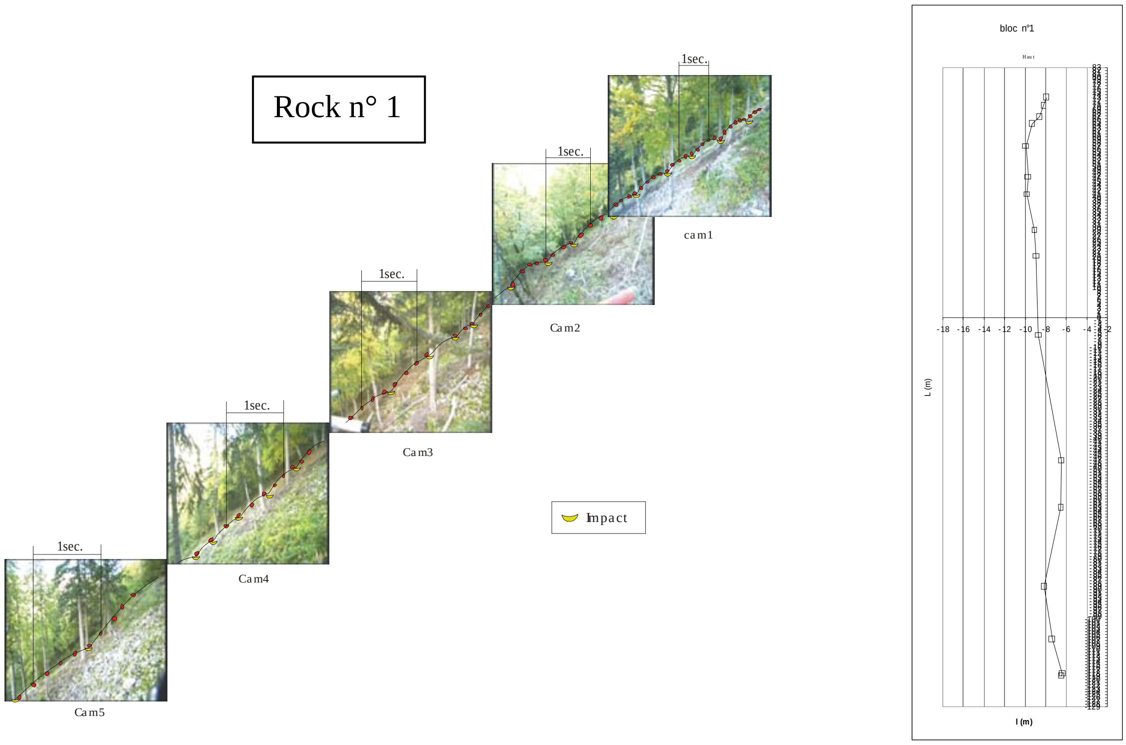


Photo 14 Examples of film’s pictures concatenation in one global picture and associated trajectory.

CONCLUSIONS

This article has presented the first step of a European research project on the understanding of the role played by forest stands against rockfalls propagation. Few conclusions can be made after this first year.

The methodology developed by the Cemagref to gather data coming from rockfall real size experiment is operational and have been tested and used successfully for the first serial of experiments(for the non forested site) programmed within the ROCKFOR project. So, the second phase of this project has been initiated and the second serial of experiments, for the forested site, will be made in June 2002.

This work demonstrates that is possible to use a "soft technology" on non permanent experimental site to get kinetic data with a good accuracy. So, such experiments are reproducible on other sites with different slope values, soil and land use conditions.

In parallel of this work, the concept for tree mechanical behaviour modelling during a dynamic solicitation has been formulated and a first mathematical expression of this model has been elaborated. This model will be calibrated with the data coming from the second serial of real size experiments programmed in June 2002. Since this model will be robust, it will be integrated in rockfall trajectory simulation model in order to realize virtual experiments.

All the data coming from the real size experiments will be available the 1rst January 2005 on the web site of the ROCKFOR project. Up to now and due to the rockfall trajectory simulation models benchmarking organised by the French minister of environment it was not possible to present in detail the first set of data (gathered and calculated) coming from the first serial of real size experiments.

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