

# LIDAR APPLICATIONS TO ROCK FALL HAZARD ASSESMENT IN VALL DE NÚRIA

Marc Janeras<sup>1</sup>, Maria Navarro<sup>1</sup>, Georgina Arnó<sup>1</sup>, Antonio Ruiz<sup>2</sup>, Wolfgang

Kornus<sup>2</sup>, Julià Talaya<sup>2</sup>, Marcel Barberà<sup>1</sup>, Ferran López<sup>1</sup>

<sup>1</sup>RSE, Aplicaciones Territoriales, S.A. <sup>2</sup>Institut Cartogràfic de Catalunya

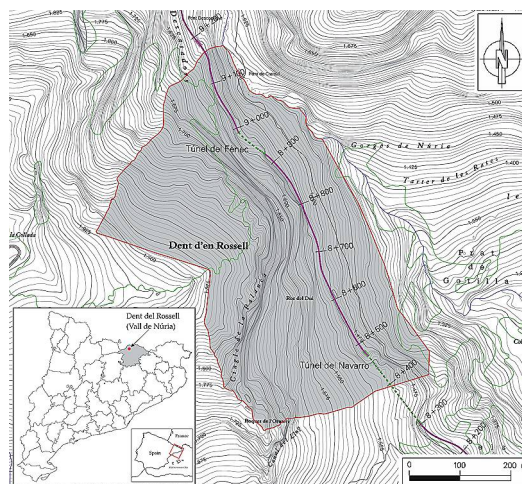
## ABSTRACT

Vall de Núria and the Ribes-Núria cog railway track are situated in a high mountain landscape that presents high sub vertical walls with unevenness of about 300 m and is subject to natural dynamics where geomorphologic destructive processes take place such as rock falls. Dent d'en Rossell is one of the most active areas in the whole valley. In order to improve the safety of the cog railway track new techniques have been incorporated into hazard assessment studies such as airborne and terrestrial lidar. The use of these methods allows modelling the topographic surface in a very accurate way and has allowed us to develop a specific working methodology to estimate the geologic risk over the cog railway related with rock fall instabilities, which would be too expensive to carry out by using conventional topographic techniques.

## INTRODUCTION

Vall de Núria and the cog railway track are situated in a high mountain landscape subject to natural dynamics that implies relief evolution. Related with this, a lot of geomorphologic destructive and constructive processes take place. Because of morphological and geological features of Vall de Núria, one of the main geodynamical active processes with an associate natural hazard degree are rock falls.

Generalitat de Catalunya is in charge of the exploitation of the Ribes-Núria cog railway since 1986. Since then, the improvement in safety has been continuous. RSE and ICC have carried out different projects in this area. Dent d'en Rossell is strongly affected by mass movements. It is an extremely steep slope to the West of Vall de Núria around the Fenech railway tunnel (*Figure 1*). This rocky slope presents high sub-vertical walls that attain unevenness of about 300 m. Lately, several rock falls have occurred in this area that have affected the cog railway track. The main recent events took place in October 1993, March 1994, May 1996, August 1999, March 2003, April 2003 and June 2003. The last three events will be studied here. To improve hazard and risk assessment studies new techniques have been essential. One of them has been Light Detection and Ranging or lidar (Ruiz et al., 2004). It allows modelling the topographic surface in a very accurate way to obtaining a DEM (Digital Elevation Model) or a true 3D surface and to estimate the geologic risk over the cog railway related with rock fall instabilities.



**Figure 1.** The study area in grey, the railway in purple and the tunnels in green.

## OBJECTIVES

The aim of this work is to analyse the advantages and possible restrictions that could appear in the application of the DEM obtained by lidar, in front of other conventional methods used in rock-falling hazard assessment. The determination of geologic risk related with any type of phenomenon must be necessarily deduced from three stages:

- 1) Detection of potential instabilities areas.
- 2) Evaluation of hazard, taking into account the frequency and magnitude of the phenomenon.
- 3) Reckoning of the vulnerability existing in the studied area.

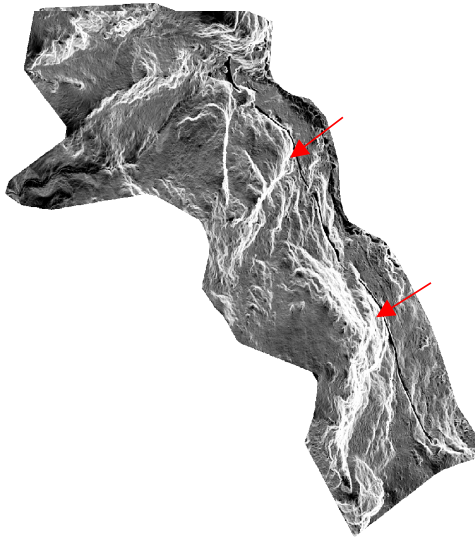
Lidar can be especially useful in stages 1 and 2. This paper shows how lidar allow us to get better results in rock fall hazard assessment by confronting the results derived from three different DEMs of Dent d'en Rossell. The first one was been obtained by photogrammetry from 1:30000 aerial photographs and has a mesh size of 15 m. The other two come from the DEM obtained by a combination of terrestrial and airborne LIDAR. They have a mesh size of 8 and 2 m respectively. This work does not try to deepen in the knowledge of rock fall dynamics in Vall de Núria and neither to evaluate the hazard and risk related with them. The results will be compared to some of the rock falls occurred in Dent d'en Rossell on 2003.

## LIDAR: DATA AND METODOLOGY

The airborne lidar survey was done on July 28, 2003 and consisted of seven parallel strips with 20% overlap that covered the Núria River valley. These strips had a half scan angle of 7° (setting A in table 2). The almost vertical pointing of view reduced the likelihood of occlusions due to the mountains at the bottom of the canyon. Two additional parallel strips were flown over each side of the river to get more points on the steep slopes of the mountains. These additional two strips had a half scan angle of 20°, the maximum allowed by the instrument (setting B).

	Setting	
	A	B
Velocity (knots)	120	120
Half scan angle (degrees)	7	20
Scan frequency (Hz)	35	20
Pulse repetition (Hz)	25,000	25,000
Height above ground (m)	1300	1300
Strip overlap (%)	20	-
Ray divergence (mrad)	0.2	0.2
Point distance along track (m)	0.88	1.54
Point distance across track (m)	0.89	1.51
Footprint (m)	0.260	0.260

**Table 1.** Lidar survey parameters



**Figure 2.** Slope map of the 2.5D surface model. The arrows show the railway track.

the presence of vegetation in this very steep terrain confused the program very often and an intensive editing work was required. The editing process continued until the resulting 2.5D model was considered to be an acceptable representation of the bare earth surface, within the limitations of 2.5D surface models. This intermediate surface (*Figure 2*) was employed for two different purposes:

- 1) to detect the areas where the density of aerial data was too low or where data gaps appeared due to occlusions (*Figure 3*). A terrestrial lidar survey campaign was carried out to cover these areas
- 2) to improve the orientation of the terrestrial lidar data.

Last echo airborne lidar points were classified into ground and non-ground points with the help of TerraScan software (Terrasolid, 2004a). A triangulated irregular network (TIN) was computed with TerraModeler (Terrasolid, 2004b) taking into account only the ground points as a first approach to the terrain model. As most of the computer programs usually used in terrain modelling, TerraModeler builds 2.5D surface models. The name 2.5D is applied in computer graphics to those special kinds of surfaces where each point in the horizontal domain has only one corresponding elevation. Therefore, the elevation in these surfaces is a function of the (x,y) coordinates. This surface model is not appropriate to represent overhang areas where a single (x,y) point can have three corresponding elevations.

Usually, after automatic classification some editing is required to remove residual vegetation that the automatic classification has wrongly classified and that has been included in the terrain model. The

Five sites were selected to station the terrestrial scanner in front of the areas showing important gaps in airborne data. The terrestrial lidar survey took two days, from September 8 to 9, 2003. Target reflectors were installed and their coordinates were measured with GPS and total station. The known coordinates of the targets allowed for a first approximation to the point cloud orientation of each scan but, as they were closer than the area to measure, the angular accuracy of this orientation was poor. In order to improve this preliminary orientation, surface matching was employed.

A grid surface was computed for each terrestrial scan scene and another was computed from the aerial points classified as ground in the 2.5D model. This last surface was considered as the reference surface. The orientation of each terrestrial scan scene was adjusted to match the reference surface obtained from the airborne lidar points. For each terrestrial lidar point cloud a translation and a rotation were computed to minimize the distance between the corresponding scan surface and the reference surface. This processing was done with Polyworks (Innovmetric). Once the orientation of the terrestrial points was refined they had to be classified but the available software was not able to process data in almost vertical walls. The classification algorithm filter assumes that the terrain slope is not too high and those points that increase the surface slope over a certain threshold are supposed to belong to the vegetation. This assumption failed completely in this area. To circumvent this limitation a global rotation was applied to all the lidar points to reduce the average slope of the terrain. The point cloud was rotated 30° around an axis approximately parallel to the railway track. After that, it was possible to add points to the previous set of ground points by a fast editing procedure using the standard tools available in TerraScan. The amount of available ground points in areas with data gaps increased and the model improved (*Figure 3, right*). After the editing, the inverse rotation was applied and a true 3D triangulated surface model was computed with all the points classified as ground.

## GEOLOGIC AND GEODYNAMIC CONTEXT

### Lithology and structure.

Vall de Núria is in the axial zone of the Pyrenees where the oldest materials of the mountain system outcrop. They are metamorphic rocks that correspond to gneiss of the Carançà unit. The regional geologic structure is strongly affected by both Hercinian orogen and alpine orogen. Orientation and spacing measures of several joints and its statistical treatment have permitted to identify the main discontinuity sets (Rendon, 2004) (*Table 2*). The intrinsic features of metamorphic rocks such as gneiss and the three discontinuity sets of the rocky mass condition the relief morphology of the valley, which is particularly steep in Dent d'en Rossell. The zone is also characterized by structural trends which form terraces and landings of metric order.

Discontinuity set	Type	Mean azimuth	Mean slope dip	Mean spacing (m)
F1	Diaclase	080	65	0.3
F2	Diaclase	020	70	0.4
F3	Foliation	260	30	0.5

**Table 2.** Mean orientation and spacing of the discontinuity sets detected in Dent d'en Rossell (from Rendon 2004).

### Rock fall risk in Dent d'en Rossell.

Rock falling is the result of an evolution process in which a lot of factors take part (lithology, discontinuities, external geodynamic phenomena such as frost shattering and root growth). Every rock fall is unique and takes place suddenly because it requires very particular conditions to occur. In Dent d'en Rossell, the orientation of some vertical slopes and certain discontinuity sets bring about the existence of potential instabilities areas that can unchain rock falling. The relationships between them generate individualized blocks of a large range of dimensions. The more recent evidences of activity related with rock fall instabilities in Dent d'en Rossell are those occurred in March, April and June, 2003.

**March 3, 2003 event:** The falling of a rock mass of between 5-8 m<sup>3</sup> of volume caused several damages to the cover structure of the North entrance of Fènech tunnel and to the cog railway. From the observed

evidences the starting point was determined to be one hundred meters above the cog railway. The path tracked by the mass mobilized followed a structural tread until it arrived on top of the cover, where the most of the mobilized mass was deposited (rocks, soil and vegetation). The path continued downhill crossing the Queralbs-Núria route until the Núria River. The maximum volume of the blocks stopped along the path was about  $0.5 \text{ m}^3$ .

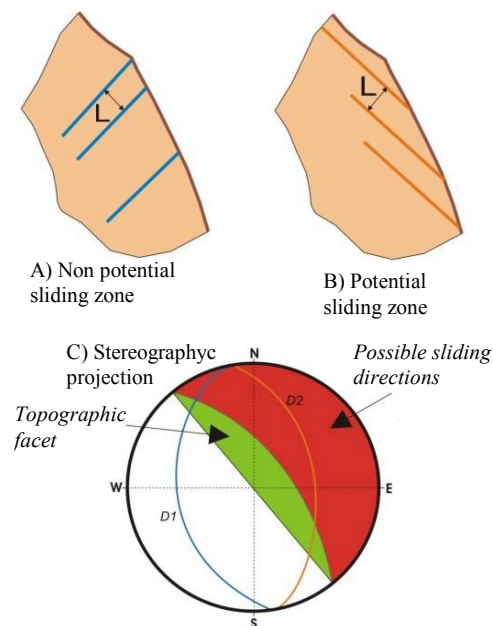
**April 4, 2003 event:** At 5:55 am a rock mass fell off from a vertical slope placed 120 m above the KP 8+500 of the railway track, near Navarro tunnel. The massif in this area is strongly affected by F1 and F2 discontinuities sets. The estimated starting volume was about  $54 \text{ m}^3$ , or 130 tones. The path, which was quite rectilinear, crossed the cog railway track, the Romeu route, and reached the Núria River. The great magnitude of this event used up the whole absorption capacity of the upper three dynamic barriers installed 4 years ago, which were 6 m tall. The rock fall caused important damages to the railway track and the wall under it. A part of the total mobilized mass stopped on top of the upper terraces of the slope, and behind the dynamic barriers destroyed by it. Some other part stopped on the railway track and the most of it was scattered downhill creating a talus scree beneath the railway track. A little part reached the Núria River.

**June 15, 2003 event:** At 11:30 pm a rock fall took place in the talus adjacent to the cog railway track near the South entrance of Fénech tunnel (KP 9+050). The starting zone was placed 8 m above the track. The rock fall path followed a rectilinear path, crossed the Romeu route and reached the Núria River. The starting volume was estimated about  $17 \text{ m}^3$ , which would be equivalent to 40 tones. The mobilized mass directly affected the railway platform where about  $8 \text{ m}^3$  was deposited. The rest of the mobilized mass created a blocks and soil deposit scattered down between the railway track and river, opening a corridor among the forest. The Romeu route got blocked by trees, blocks and soil accumulation.

## HAZARD ASSESSMENT

### Detection of potential instabilities areas

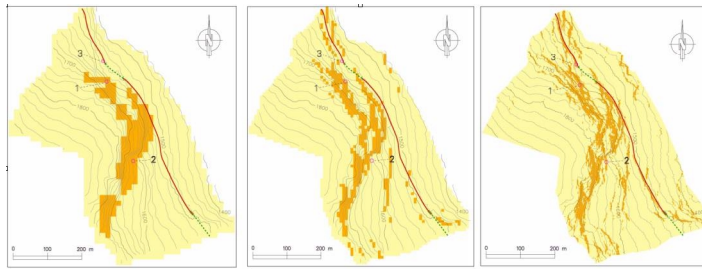
One of the first tasks to do in rock fall hazard assessment at Dent d'en Rossell is to identify potential instabilities areas, in which lidar technology can contribute to obtain substantially improvements. One of the primary uses of DEM is to analyse the interaction between topographic surface characteristics (relief morphology, slope, orientation, etc.) and structural characteristics of the rocky mass (existence of one or more discontinuity sets, orientation and slope dip of these, etc.). In order to cross this data research software developed by CREALP (Centre de Recherche sur l'Environnement Alpin) has been used. It was developed as a working tool in Matterrock Methodology (Rouiller, J.D., Jaboyedoff, M., et al. 1998), which allows locating favourable instabilities areas using a DEM. The main principle this software takes into account is related with the necessary conditions for the orientation and the slope dip of a determinate plane of discontinuity that could trigger a rock fall, depending on the orientation and the slope of the topographic surface. Figure 4A shows an example where the relation between the topographic surface and the discontinuity set D1 makes rock falling improbable. Figure 4B shows a case where the conditions are favourable to triggering of a rock falling. Once the data defining the orientation and the slope dip has been introduced, the program analyses the DEM cell by cell and assigns to each cell a value of 1 or -1 according to instability probabilities. All 3 DEMs of different mesh size have been crossed with the same structural data. For the slope orientation in Dent d'en Rossell, we have only considered data corresponding to families F1 and F2 because family F3 plays a negligible roll in slope stability in this sector. The results are shown in figure 5,



**Figure 4.** Examples of non-potential (A) and potential (B) sliding zones in section. L is the spacing between two discontinuities. C: Lambert stereographic projection of possible sliding directions (in red) taking into account the topographic orientation (in green). Modified from (Jaboyedoff et al., 2003).



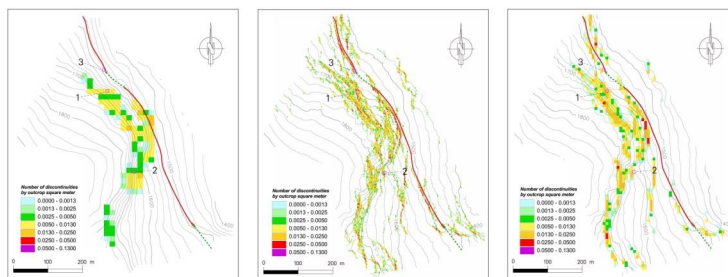
which shows zones prone to instability and the starting zones of the rock fall events from March, April and June 2003.



**Figure 5.** Instability zones (in orange) obtained from 15, 8 and 2 m meshes. The numbers represent the starting points of rock falls from March, April and June 2003, respectively.

the railway cog and this slope vanishes in the 15 m mesh. With lidar DEMs (*Figure 5, centre and right*), we can see that there is a difference in the distribution of the favourable areas. In the 2 m mesh, the 3 areas that originated the rock fall events of March, April and June are detected, while the 8 m mesh only detects the area that triggered the March event. The relief of Dent d'en Rossell presents a characteristic morphology and dimensions that are modelled more accurately by the 2 m mesh. For example, the slope adjacent to the railway track is clearly visible in the 2 m mesh only.

#### Hazard evaluation at the source area

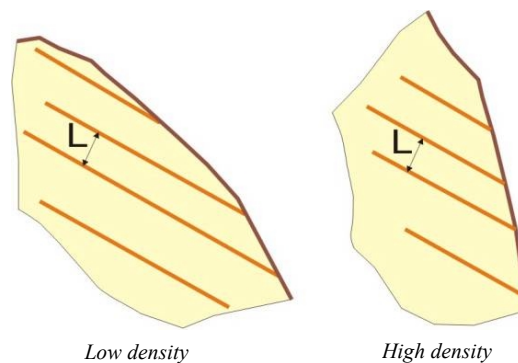


**Figure 6.** Number of wedges by square meter obtained from 15, 8 and 2m meshes. Numbers 1, 2 and 3, represent the starting points of rock falls from March, April and June 2003, respectively.

equivalent to the maximum hazard value (Jaboyedoff, M., et al. 1999), even though rock fall hazard is not only defined by the structural features of the rocky mass, so to determine the hazard properly it is required to adjust the calculated value taking into account other parameters such as lithology, climatic conditions, the volume of the mobilized mass, etc. This approach could be applied to wedges in a similar way. The same research software used to detect potential instabilities areas has been used here to calculate the average number of wedges by unit cell of DEM. The program assumes infinite discontinuities, so the only thing that has to be known is the mean spacing ( $L$ ) of each discontinuity set (*Table 3*). The average number of wedges by unit cell has been converted to number of wedges by square meter of outcrop, so that the final results are quite close to the real ones (*Figure 6*). In the figure we can see also that the number of wedges intercepting the topographic surface by square meter of outcrop is slightly higher as the mesh size decreases. This is due to the smoothing effect of the relief that occurs as the mesh size increases because with a certain orientation of the family sets, the density depends directly on the terrain slope (*Figure 7*). The 2 m mesh reproduces better the real slope of sub-vertical walls, while the 15 m mesh smooths this

Figure 5, left, shows that at 15 m grid step, rock falling areas group themselves homogenizing the results, even though in all three cases the rate between favourable areas and unfavourable ones is almost constant. Using lidar DEMs no new source areas appear but they redistribute. Only the starting areas of the April and March events lay inside the predicted instability areas according to 15 m mesh model. Probably this is due to the fact that the June event was produced in the slope adjacent to

Once the average characteristics of the discontinuity sets have been established and potential instabilities slopes have been detected, the probability to find at least one discontinuity in a given surface can be evaluated using the average number of discontinuities contained inside this surface (Rouiller, J.D. and Jaboyedoff, M., 1998). This probability can be used as a first quantification of the hazard. The value obtained is



**Figure 7.** Relation between topographic slope dip and number of discontinuities intersecting the surface.

relief, and the derived slopes are smaller than the real ones. Taking all these facts into account we can conclude that using 15 m DEM we are underestimating the risk. A visual comparison between 8 and 2 m DEMs shows that the last one reproduces better the topographic surface and we can expect better results with it.

## **Hazard assessment from rock fall models**

### ***Introduction***

At this point we want to compare the results of rock fall simulation with 3 different DEMs. Computations are done with two and three-dimensional models. 3D models calculate rock fall trajectories on a DEM and allow obtaining the distribution of kinetic energies, maximum bouncing heights and stop points. 2D models work on established topographic profiles and allow obtaining the statistical distribution of the same variables along a path. In this case we have been working with two commercial models in 3D and 2D. Both of them have been calibrated and validated with data from the 3 rock fall events from 2003.

### ***Rock fall models***

Three-dimensional programs allow making numerical calculus from physic laws, which relate mechanical parameters of the slope with the block kinematics. This software allows calculating the distribution of rock trajectories, kinetic energies by unit of mass, bounce height and stopping points from a DEM. The programs allow to simulate a high number of rock falls and to identify the most suitable areas to build protection systems. Different types of terrain must be distinguished over the DEM and the parameters that define their mechanical behaviour must be defined. These are the coefficient of restitution of normal energy ( $R_n$ ), the coefficient of restitution of tangential energy ( $R_t$ ) and the friction coefficient of the rolling boulders ( $k$ ). It is also necessary to introduce three geometric parameters (limit angles), which determine the changes in the type of movement along the paths followed by the rocks. Variations in the slope and in the way followed by the blocks imply changes between flying and colliding phases.

The two-dimensional model requires fixing the path, but on the other hand, allows doing a full statistical analysis of the movement variables along this path, as a function of the relief and the terrain type parameters, as in the 3D model. As a consequence, the results of both two models are complementary.

Model calibration allows assigning the parameters a value that reproduces the specific behaviour found in the studied sector. Once calibrated, the models will predict future events that could happen in the area. In this case, calibration of the model has been possible from the 3 events from 2003.

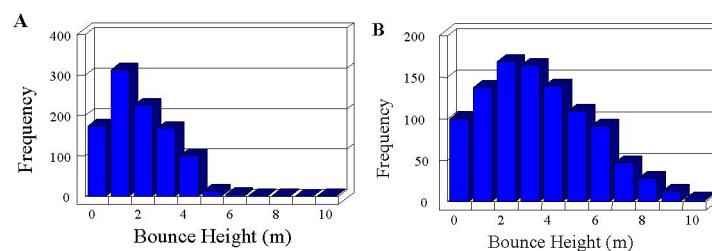
### ***Comparative analysis of DEM***

Known events from 2003 have been simulated with the 3 previously defined meshes: 15, 8 and 2m so we can find which topography compares the better with field observations. The results obtained for the March and April events are shown in figures 8 and 9.

We can appreciate that the trajectories simulated from lidar topography show a better adjustment to the channel followed by the rock fall, as can be seen in figure 9 by the sinuous trace of the event from March. The 15 m mesh shows a more rectilinear path because of the smoother relief. It is remarkable that as the mesh size reduces, the dispersion area increases, due to the rise in terrain roughness. Evidently, as we increase the mesh size, the smoother and more simplified the topography appears: the 15m mesh model

cannot distinguish so many changes between rolling and flying phases along the path, and this was also found by (Abellán 2003).

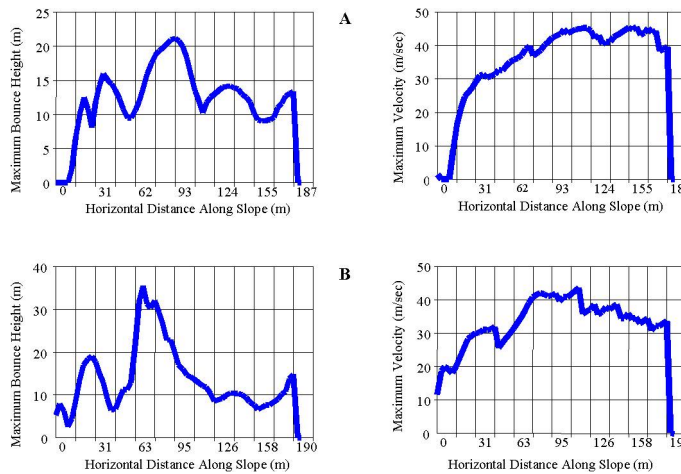
As we can observe in figures 8 and 9, contour lines derived from lidar define better the different morphologies, representing boundings and terraces in the trajectory that have a large impact on rock fall dynamics. In any case, the path is the same because the model reproduces trajectory dispersion with little variation on initial movement conditions. The results on the stopping points of the April 2003 event (*see figure 10*) show less differences between meshes of 15 and 8m, while major accuracy can be appreciated on the 2m mesh results. This last one shows a concentration of stopping points in zones where rock blocks were observed in the field, as the railway platform, while the other two only show block concentrations in the barriers. With lidar models there is an improvement on the results accuracy. One reason is that it is required to choose a convenient mesh size to represent the relief. In this case, the width of the railway cog platform is about 4 m and only the 2m mesh can represent the platform accurately enough. In this sense, we tried a simulation with 1m mesh. At this scale the model shows very steep slopes, which forces the trajectories to bounce continuously with constant oscillations of the slope along



the path and behaves far away from reality. Moreover, it is an incommodious scale to work with, because it increases the processing time too much.

Next, relevant aspects in the results obtained with 2D numerical models are commented. The event from April 2003 has been simulated to obtain the bounce height distributions for a medium slope site at 1560 m of elevation. The simulation has been done using the 2 and the 15 m meshes (*see figure 11*). As was found with 3D models, in the smooth topography of 15 m mesh, the rolling and colliding movement dominates, in contrast to the 2 m mesh from which higher bounds are derived. The 2 m mesh adjusts much better the profile of movement variables (height and velocity) along the path, because it describes better the highest slopes, as the one on one side of the railway platform. This allows a better placement of defence works against rock fall in points of maximum efficacy. In particular, it is convenient to position barrier defences (which have a certain capacity of energy absorption) in points of low bounce height and velocity, so that they will be able to intercept the maximum number of blocks and brake a larger rocky mass. When we compare velocity profiles (*figure 12*) we can observe that in the 15 m mesh there is an

increment on velocity once the railway is passed in contrast with 2 m mesh. In this last case, the model represented smaller bounding morphologies where the blocks impact on the terrain, loose kinetic energy and reduce its velocity.



**Figure 12.** Bouncing height and velocity along the path for 15 (A) and 2 m (B) meshes.

Three-dimensional models can be considered a useful tool to predict the distribution of possible trajectories, kinetic energy, bouncing heights and stopping points of rock fall, whenever we have enough historic events to calibrate the model properly. As it has been demonstrated, lidar technology allows working over high-resolution topographies. This improves three-dimensional model utilities in front of the arguments exposed by (Krauter & Spang, 2001). Calculus algorithms have been developed to model accurately rock fall dynamics. Even wide spread commercial models present some limitations which difficult taking maximum profit from lidar topography. They represent the movement in a very

simplified way and the results are usually extreme and mean values. New available resolution from lidar topography will probably push the development of new statistical treatment techniques in a cell by cell basis that would be more useful in the near future.

## CONCLUSIONS AND RECOMMENDATIONS

Incorporation of lidar technology to the study of rock fall allows putting in practice a specific analysis methodology of susceptibility and hazard areas detection. This was not possible with conventional terrain models.

The DEM obtained with conventional methods, with a 15 m mesh size smoothes the relief too much and this yields to very different results that reduce the security factor in potential instabilities areas detection. The calculus on lidar models reproduce better the rock falls and detects more accurately potential instabilities areas.

The working scale has a large impact in modelling results. In the case of Dent d'en Rossell, results obtained with a 2 m mesh DEM fit better to the observed events in this sector. In another area the optimal mesh size could be different.

Commercial rock fall simulation programs can reproduce quite well the rock fall events, whenever they are properly calibrated with data enough from known events.

Three-dimensional models are a useful tool to predict the distribution of trajectories, velocities and heights of future rock falls but, they still have limitations that difficult taking the maximum profit from lidar topography.

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