

# An empirical approach to rockfall fragmentation

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**ABSTRACT:** The impact-induced rock mass fragmentation in a rockfall is analyzed by comparing the In Situ Block Size Distribution (IBSD) at the cliff face and the Rockfall Block Size Distribution (RBSD) on the slope. The IBSD is extracted from a Discrete Fracture Network generated using a Digital Surface Model of the cliff obtained with digital photogrammetry. The RBSD is obtained directly by measuring the blocks deposited on the slope. The IBSD and RBSD are well fitted by exponential and potential functions, respectively. We present a procedure to derive the RBSD from the IBSD using a fractal fragmentation model based on Perfect (1997) and considering a survival rate of the blocks impacting on the ground surface.

## 1 INTRODUCTION

The fragmentation of the rock mass during a rockfall is a complex phenomenon poorly understood. It involves the separation of a rock mass into several smaller pieces upon the first impact(s) on the ground surface, leading to independent trajectories of the resultant blocks. The fragmentation causes the redistribution of the initial rock mass; it affects the runout distance, the impact energy and consequently, the rockfall hazard.

A rock mass detached from the slope face at a rockfall event is composed of intact rock blocks and discontinuities. The range of sizes of the blocks is characterized by the In Situ Block Size Distribution (IBSD). After the first impact(s), the disaggregation of the rock mass along preexisting discontinuities and the intact rock breakage modify the original distribution of the block volumes resulting in a new one, the Rockfall Block Size Distribution (RBSD).

The scope of this work is twofold: the analysis of the fragmentation process by comparing the changes between the IBSD and the RBSD; and the development of a procedure to obtain the latter from the former, based on a fractal fragmentation model. The model is based on the one proposed by Turcotte (1986) and Perfect (1997), and it has been adapted for rockfalls. The application of this model requires the definition of the initial IBSD and 3 parameters which are:  $S_r$ : Survival rate: that expresses the proportion of the blocks from the IBSD that remain unbroken after the impact(s) on the ground;  $P_f$ : Probability of failure (Perfect,1997), that determines the number of new blocks

generated by breakage of each original block; and *b*: Scaling factor: that is a geometric relation between the original blocks and the new generated blocks.

## 2 CASE STUDY: THE CADÍ ROCKFALL

The proposed procedure has been applied in a large rockfall event occurred in November 2011 in the Cadí massif, Eastern Pyrenees. The rockfall detached a mass of about 10000 m<sup>3</sup> (Fig. 1).

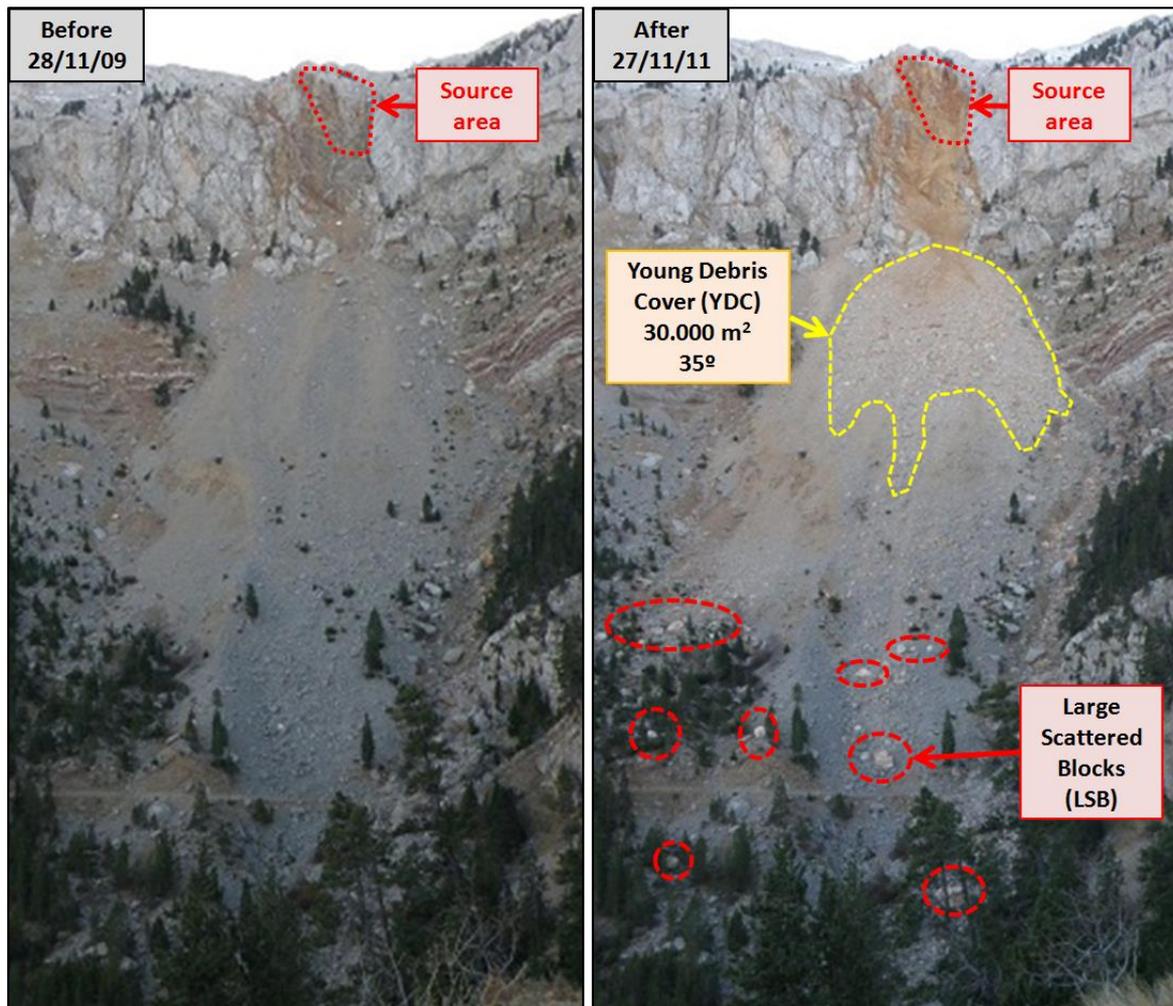


Figure 1: Pictures from before (28/11/2009) and after (27/11/2011) the rockfall event in the Cadí ridge, Eastern Pyrenees, Catalonia, showing the source area and the deposited rocks.

### 2.1 Rockfall Block Size Distribution

Mid to large-size fragmental rockfalls often produce a more or less continuous cover of young smaller debris and larger scattered blocks. It may have a large extent and display progressive downhill increase of the average block size. Because of this, obtaining the RBSD may become a challenging task. We have developed a methodology to generate the Rockfall Block Size Distribution (RBSD) (Ruiz et al., 2015) which includes two complementary activities: a) the selective sampling of the young debris cover (YDC); and b) the systematic measurement of the Large Scattered Blocks (LSB). The methodology is summarized in Fig. 2.

First, the YDC is divided into homogeneous zones (in this case, A1 to A3) of similar average block size based on visual field observation and orthophoto interpretation. At each zone, several

sampling plots are selected in which all blocks bigger than  $0.015 \text{ m}^3$  are measured, thus giving the block size distribution of the plot. The sampling plots have a square shape and their size increases with the size of the blocks inside. The Large Scattered Blocks are georeferenced and measured one by one. Three lengths more or less orthogonal to each other are measured at each block to estimate the volume, assuming that the shape of the blocks is prismatic.

Several constraints must be overcome. In case that rockfall fragments accumulate over a previously existing talus deposit, a key issue is differentiating young from old rock fragments. When the reconnaissance is made shortly after the occurrence of the rockfall event, this should not be a difficulty. New blocks usually show distinct fresh broken surfaces, faces with stained coatings and clay fills, and bright colours. If the YDC is a thick continuous cover, then the counting becomes uncertain unless the thickness of the cover can be clearly determined. All the block size distribution obtained from the YDC and from the LSB are used to obtain the final RBSD representative of the whole deposit. Further details of this procedure is found in Ruiz et al. (2015).

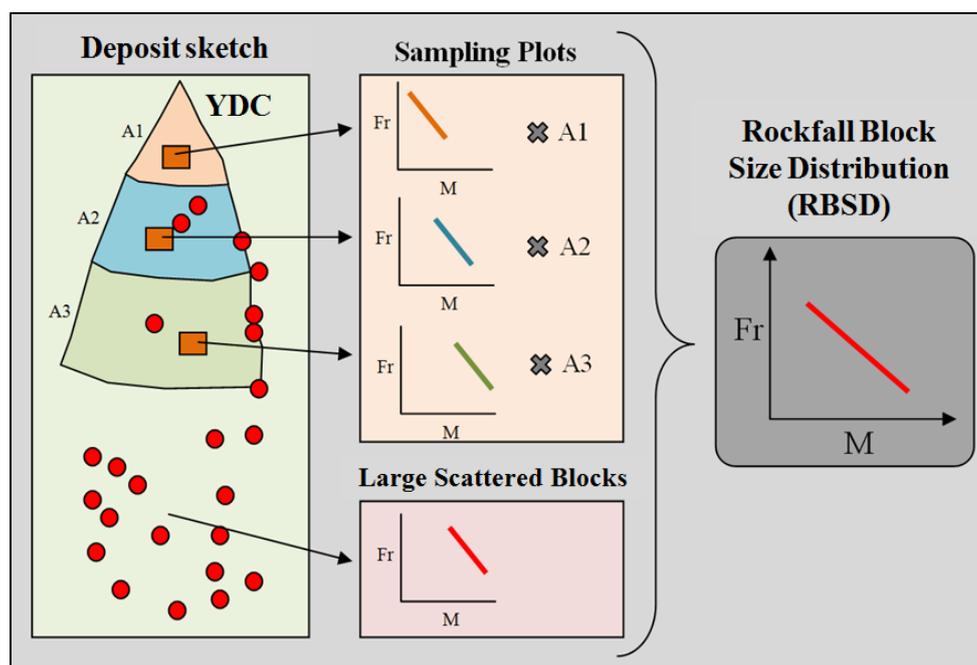


Figure 2: Methodology to obtain the RBSD in large rockfall deposits (Ruiz et al., 2015).

The homogeneous zones defined, the location of the sampling plots, the location of each Large Scattered Block measured and the source area, is represented in the Fig. 3, overlapped to the contour lines and the orthophoto of the zone. The plot in the right side of the Fig. 3 shows the frequency - block size relations obtained in each sampling plot and in the LSB measurements. In the same plot, the final RBSD is presented in red color. Notice that all the block size distribution obtained from the deposit can be well fitted by power laws using linear regression or the maximum likelihood methods, with values of  $\chi^2$  test close to 0 (0.01 - 0.03) (Ruiz et al., 2015). The final RBSD can be well fitted with a power law whose exponent is 1.27. Sampling plots 1, 2, 3 and 4 are located in the highest and middle zones in the YDC and contain mostly the small and medium size boulders. Sampling plots 5 and 6, which are located at the lowest part of the YDC, have a predominance of big blocks. Finally, the LSB contain the biggest boulders measured in the field (Fig. 3). The total rockfall volume calculated from the measurement of the blocks is close to  $8000 \text{ m}^3$ . The real volume must be larger because blocks smaller than  $0.015 \text{ m}^3$  were not measured.

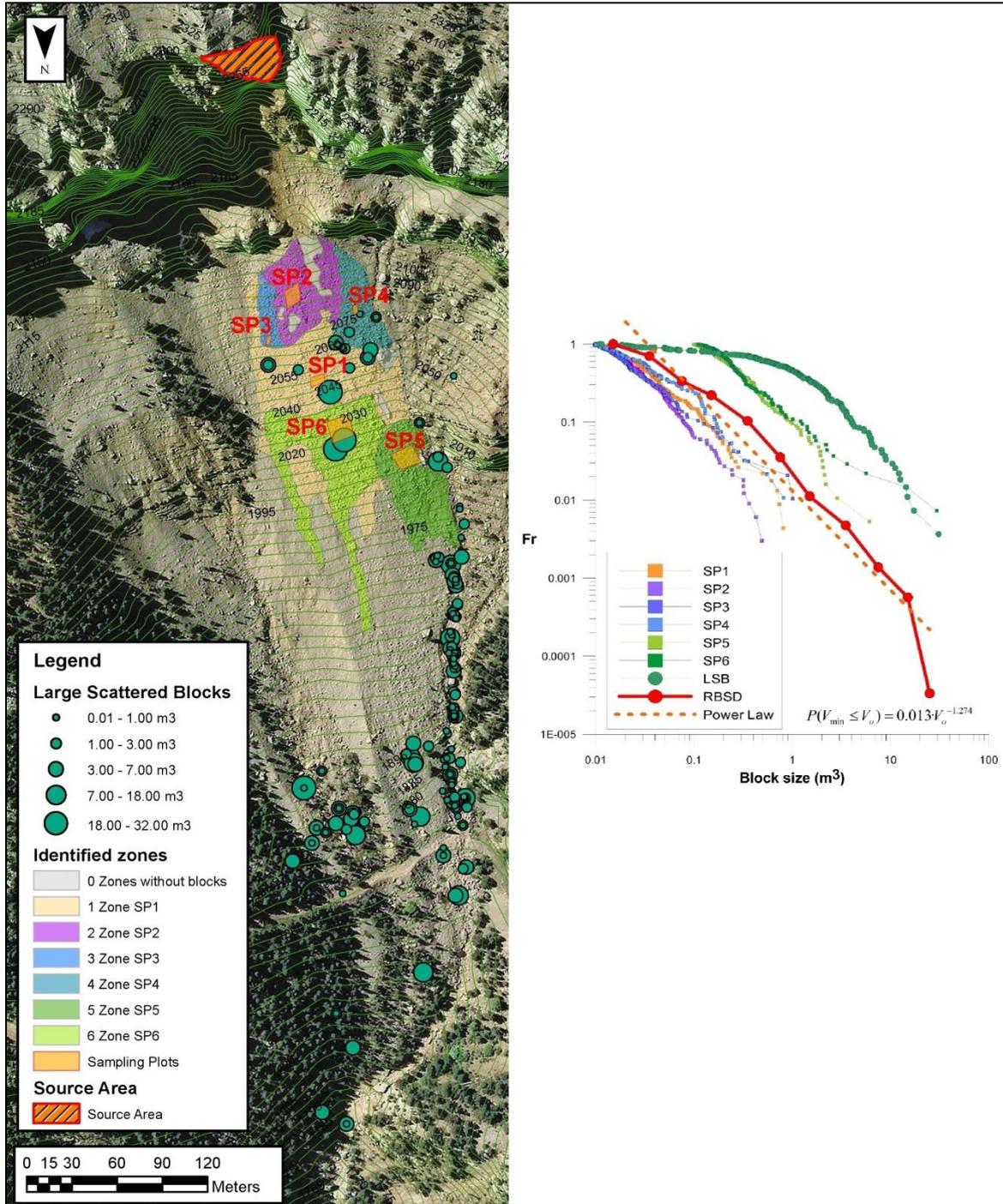


Fig. 3. Location of the homogeneous areas, sampling plots, and individual large scattered blocks measured blocks. (left) and the RBSD obtained (Ruiz et al. 2015)..

## 2.2 In Situ Block Size Distribution estimation

It may be expected that the volume of the detached mass and the ISBD had a significant influence on the RBSD. We used photogrammetric techniques with the software VisualSFM to obtain the 3D Digital Surface Model (DSM) of the rockfall scar based on photographs. The latter were taken with a camera Nikon D90 with a focal length of 60mm and a resolution of 4288x2848 px (12Mp). The first step was to reconstruct the detached rock mass volume by subtracting the DSM of the scar, from

the available topographic map at scale 1:5000 (prior to the rockfall event) and field observations. Then, we used the DSM, texturized with the pictures, to identify the fracture pattern of the in-situ rock mass. We identified 5 joint sets using both semiautomatic and manual techniques. The fracture pattern is applied to the missing rock mass volume, which is cut assuming infinite persistent joints, and finally the IBSD is obtained. We used two different volumes: a) the reconstructed missing irregular volume of the detached mass ( $\sim 10000 \text{ m}^3$ ) and b) a prismatic shape with the same volume, to simplify the cutting tasks. The difference between the total volume measured in the rockfall source and the measured in the deposit ( $2000 \text{ m}^3$ ) can be explained by the proportion of blocks smaller than  $0.015 \text{ m}^3$ , which were not measured. Figure 4 shows the fracture pattern in the prismatic and reconstructed volumes. We generate four IBSD with different assumptions: prismatic and irregular shape; volume of  $10000 \text{ m}^3$  and  $5000 \text{ m}^3$ ; and 4 and 5 joint sets. The IBSD obtained are plotted in the right side of the Figure 4. All of them can be fitted by exponential laws with coefficients of determination close to 1.

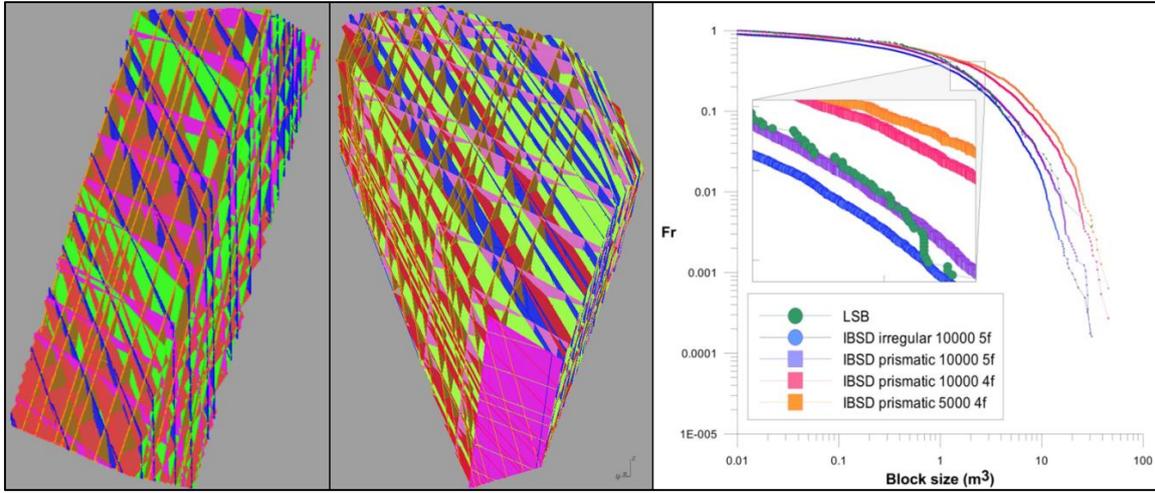


Figure 4: IBSD generated taking a prismatic volume (left) or a reconstructed irregular volume (center) of the detached rock mass, and the corresponding IBSD (right) considering 4 or 5 fully persistent joint sets.

### 3 FRAGMENTATION MODEL

The proposed fragmentation model followed is based on a generic fractal fragmentation model (Perfect 1997). It aims at generating the RBSD from the ISBD. The model of Perfect (1999) considers a cubic block of unit length that breaks into small pieces following a power law. Fractals are hierarchical, often highly irregular, geometric systems generated using iterative algorithms with relatively simple scaling rules. The size distribution of elements in a fractal system is given by (Eq. 1):

$$N(1/b^i) = k[1/b^i]^{-D_f}; i = 0,1,2..\infty \quad (1)$$

Where  $N(1/b^i)$  is the number of elements at the  $i$ th level of hierarchy;  $k$  is the number of initiators of unit length;  $b$  is a scaling factor  $>1$ ; and  $D_f$  is the fragmentation fractal dimension, which may be defined as:

$$D_f = 3 + \frac{\log[P(1/b^i)]}{\log[b]} \quad (2)$$

Where  $D_f$  is the fragmentation fractal dimension;  $P(1/b^i)$  or  $P_f$ : is the Probability of failure that determines the number of new blocks generated by the breakage of each original block.  $P_f$  is physically related to subunit interfaces and their boundary strength. The interfaces may correspond to existing discontinuity surfaces, anisotropy or non-persistent joints (Perfect, 1997). The range for

the probability of failure is  $b^{-3} < P(1/b^i) < 1$ . When  $P(1/b^i) = 1$  and  $D_f = 3$  the whole block is broken, while for  $P(1/b^i) \leq b^{-3}$  the block remains intact.

We have adapted the fractal fragmentation model to the case of rockfalls. First, instead of  $k$  initial unit-length volumes we use the IBSD, classifying the IBSD in bins. Secondly, not all the falling blocks will break upon impact on the ground. To this purpose, a Survival rate  $S_r$ , is defined representing the proportion of unbroken blocks after propagation.

Three parameters are therefore needed to perform the model:  $P_f$ ,  $b$  and  $S_r$ . We have been calibrated these parameters in the Cadi case-study. Four different scenarios were considered, based on the number of joint sets and the shape of the detached rock mass, to generate the initial IBSD (Figure 4). We obtained a range of values: between 0.24 and 0.33 for the  $S_r$ , between 0.65 and 0.89 for the  $P_f$  and between 1.87 and 2.2 for  $b$ . We used the  $\chi^2$  test to optimize  $P_f$ ,  $S_r$  and  $b$  values and to test the goodness of the results obtaining a range between 0.02 and 0.11 for the four cases of different IBSD as input. Figure 5 shows the IBSD obtained from the irregular reconstructed volume, the RBSD measured in the field and the RBSD obtained from the Fractal Fragmentation Model (FFM) calibration. The results show that is possible to successfully generate the RBSD from the IBSD. However, the procedure followed is iterative until the fitting between both the modelled and observed RBSD is reached. Therefore, we are not yet able to produce reliable predictions. Further work, is required to relate  $P_f$ ,  $S_r$  and  $b$  to the local geological, geomechanical, and morphological characteristics of the detached rock mass and the slope.

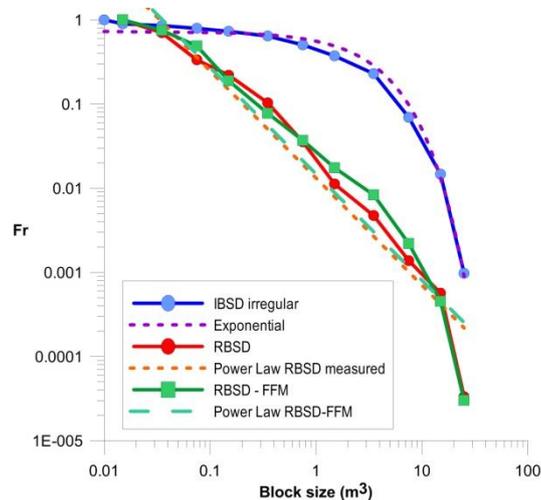


Figure 5: IBSD from the reconstructed volume, RBSD measured and RBSD generated with the Fractal Fragmentation Model (RBSD - FFM).

## ACKNOWLEDGEMENTS

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