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# 2 **Size distribution for potentially unstable rock** 3 **masses and in-situ rock blocks using LIDAR** 4 **generated Digital Elevation Models**

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## 17 **Abstract**

18 In this paper, two analytical procedures which are independent from the existence of empirical data are  
19 presented for the calculation of (i) the size distribution of potentially unstable rock masses that expresses  
20 the potential rockfall size distribution, PRSD, including big volumes corresponding to potential rare events  
21 with low susceptibility of failure and (ii) the in-situ block distribution on the slope face, IBSD. Two  
22 approaches are respectively used. The first one involves the detection of kinematically unstable surfaces on  
23 a DEM and on orthophotos and the calculation of the volumes resting on them. For the second one the in-  
24 situ block volumes formed by the intersection of the existing discontinuity sets are calculated using a high-  
25 resolution DEM. The procedures are presented through an application example at the country of Andorra  
26 and in particular at the chute of Forat Negre. The results from the first procedure indicate that it is  
27 kinematically possible to have mobilised volumes of some thousands of cubic meters, however these are  
28 considered rare events with low susceptibility of failure. The size distribution of potentially unstable rock  
29 masses for big volume events was well fitted by a power-law with an exponent of -0.5. The in-situ block  
30 distribution on the slope face from the second procedure, assuming three types of intersection between the  
31 joints of the existing discontinuity sets and two extreme cases of discontinuity persistence, was also found

1 to follow a power-law, but with an exponent of -1.3. The comparison with the observed in the field block  
2 volume distribution on the slope face indicates that in reality discontinuities have a very high persistence  
3 and that considering only their visible trace length overestimates volumes, which is conservative.

## 4 **1. Introduction**

5 Rockfalls start with the detachment of rock from a steep slope along a surface on which small or no shear  
6 displacement takes place (Varnes, 1978). This definition involves very different situations. Some basic  
7 classifications have been given by Cruden and Varnes (1996) and Hungr et al. (2014), who differentiate  
8 simple falls from the detachment of large rock masses such as sturzstroms (Hsu and Kenneth, 1975), also  
9 called rockfall avalanches (Varnes, 1958) or rock avalanches (Evans et al., 1989). The former usually refer  
10 to fragmental rockfalls i.e. rockfall characterised by one or several independently moving fragments, while  
11 the second ones to extremely rapid mass flows of dry debris created by large falls and slides. The work  
12 presented here refers to fragmental rockfalls smaller than  $10^5 \text{ m}^3$ , although the volume limit is not still well-  
13 defined in the global literature (Evans and Hungr, 1993). For fragmental rockfalls the size and velocity of  
14 the individual blocks determine the intensity of an event.

15 The quantification of the rockfall hazard requires information on the expected probability or temporal  
16 frequency of rockfalls of a given magnitude (size), usually in the form of magnitude-frequency relations.  
17 The rockfall magnitude-frequency relation is governed by many parameters. The most important are the  
18 number, dip direction and dip of the existing discontinuities and their mechanical properties, the local  
19 topographical conditions, the rock mass strength, as well as the intensity of the triggering factors  
20 (earthquake, rainfall...) and whether they are sufficient to mobilise masses of a given magnitude. When the  
21 inventory time-frame is short, information is often missing with reference to the potential for large volume  
22 events, corresponding to rare events. However, in reality, even if large failures have not occurred in the  
23 inventoried past, the possibility for future ones still exists. To check the potential for big events several  
24 researchers suggest the use of the same power-law as for smaller events (Hungr et al. 1999, Dussauge et al.  
25 2002, Guzzetti et al. 2003). However as Rohmer and Dewez (2012) outlined, the vision of very large  
26 extreme event (catastrophic) frequency being an extrapolation of the power laws fitted on small and  
27 intermediate events has been challenged in various contexts (Dorren et al. 2011, Dussauge et al., 2002).  
28 Sornette (2002) proposed viewing such catastrophic events as “outliers” from the power-law model, i.e.  
29 they deviate by an abnormal large distance from the extrapolated prediction. Thus there is the need for  
30 alternative methodologies for the detection of potential large instabilities.

31 Moreover the fragmentation effect on the initial mass and the size and velocity of the fragments are also  
32 very important for the rockfall hazard and risk assessment (Jaboyedoff et al. 2005 and Corominas et al.  
33 2012). Although fragmentation is recognised as a complex process (Chau et al. 2002; Zhang et al. 2000),

1 Wang and Tonon (2010) and Locat et al. (2006) have identified the effect of some important parameters as  
2 the presence of discontinuities and their persistence in the detached rock mass.

3 Thus a common key-point for obtaining both of the afore-mentioned pieces of information is the  
4 characteristics of the discontinuity sets that are present in the slope face. Their role is double. They delimit  
5 the potentially mobilised volumes, thus affecting the rockfall size-distribution. Additionally, they represent  
6 weak planes inside the detached rockfall masses along which those break apart upon impact on the ground  
7 surface. Although some discontinuities might not break, the delimitation of the rock blocks of a certain  
8 volume by them is related to the fragmentation effect.

9  
10 a) Volume of potentially unstable rock masses

11 A way towards the construction of a rockfall frequency-magnitude relation is the determination of the  
12 potentially mobilised volumes on the rock wall from the discontinuity network. These are the volumes that  
13 under given conditions may detach and produce rockfalls events. From now on, the distribution of these  
14 volumes will be referred to as potential rockfall size distribution (PRSD). As the distribution of the rockfall  
15 scars on the cliff face is an indicator of the rockfall activity over the last hundreds or thousands of years  
16 (Santana et al. 2012), the distribution of the potentially unstable rockfall masses on the cliff face as well.  
17 The objective of this work was the development of a procedure to calculate it. Focus is given on the  
18 possibility of having large rock masses mobilised, leading to events bigger than the observed ones so far, to  
19 calculate their volume and to provide an indication of their relative frequency in the rock mass. The PRSD  
20 is based on the detection and measurement of the size of potentially kinematically unstable rock masses on  
21 a digital elevation model of a steep slope face, where unfavourably dipping discontinuity sets are present.

22  
23 b) Size distribution of the in-situ rock blocks

24 To get a clue on the size of the fallen blocks (or rock fragments) generated by a rockfall event after a  
25 potential fragmentation, the distribution of the individual rock volumes within the detachable rock mass on  
26 the face of the slope was investigated. The individual volumes are formed by the intersection of the existing  
27 discontinuity sets (Lu and Latham, 1999; Nocilla et al. 2009; Elmoultie and Poropat 2011). This  
28 distribution is herein called in-situ block size distribution (IBSD). In rock blasting research a correlation is  
29 often indicated between the size distribution of the in-situ blocks on a rocky wall and the resultant  
30 fragments after blasting (Aler et al., 1996; Lizotte and Scolbe, 1994). This is physically interpreted by the  
31 fact that both depend strongly on the initial structure of the rock mass and the discontinuities network.  
32 Additionally several researchers have developed sophisticated models for the calculation of the IBSD based  
33 on the discontinuity network as those described by Wang and Tonon (2010) and Elmoultie and Poropat  
34 (2011). Here a simple procedure was developed, which uses discontinuity data obtained by a point cloud.

1 In a few words, the main objective of this work was the development of two simple procedures for the  
2 calculation of the PRSD and IBSD on the slope face right on the source, based on the existing discontinuity  
3 sets and their spacing. The two procedures presented here for the evaluation of the PRSD and IBSD are  
4 independent one from each other and the provided information is not interrelated but complementary. This  
5 work forms part of an on-going investigation for the correlation of the PRSD with the rockfall frequency-  
6 magnitude and of the IBSD with the fallen blocks size distribution so that they can be introduced directly  
7 into the hazard assessment; however this is out of the scope of this paper.

8

## 9 **2. Proposed methodology based on Terrestrial Laser Scanning data**

### 10 **2.1 Use of Terrestrial Laser Scanning data for rockfall investigation**

11 Field investigation may have several restrictions related to access limitations, security issues and time-  
12 consuming and labour-intensive work requirements. Due to these reasons, the massive investigation of an  
13 entire slope for its structural characterization is almost impossible, especially if intensely fractured. To  
14 overcome these limitations, we propose the use of digital elevation models DEM, obtained with Terrestrial  
15 Laser Scanner data.

16 In the last decades, important advances have been achieved in remote-sensing techniques such as  
17 Terrestrial Laser Scanners TLS or LIDAR (Light Detection and Ranging) for the capturing of point clouds  
18 representing three dimensional surfaces. TLS present the advantage of obtaining data of high precision and  
19 accuracy, easily, quickly and without access restrictions and in a digital format which offers flexibility for  
20 their massive elaboration (Slob et al., 2005; Slob and Hack, 2004). However several limitations exist as  
21 well, as for example in the case of scans that intrinsically suffer from “shadows” of missing data cast on  
22 surfaces by occluding objects (Sturzenegger and Stead, 2009; Becker et al., 2009; Lato et al., 2009).

23 The advances in techniques for capturing point clouds have been followed by the development of  
24 methodologies that exploit these high resolution data, for applications related to the evaluation of rockfall  
25 susceptibility and hazard, starting from the reconstruction of surfaces for the creation of DEM (Hack, 1998;  
26 Kemeny and Post, 2003; Kemeny et al., 2006). These applications are explicitly described at Kemeny and  
27 Turner (2008) and Jaboyedoff et al. (2012). Amongst them are: the identification and characterization of  
28 discontinuity sets (Sturzenegger and Stead, 2009; Slob et al., 2005; Kemeny et al., 2006; Jaboyedoff et al.,  
29 2009; Gaich et al., 2006; Coggan et al., 2007; Birch, 2006; Poropat, 2006; Lato et al., 2009; Jaboyedoff et  
30 al., 2004, 2007, 2009; Derron et al., 2005), the detection of rockfall scars (Guerin et al. 2014; Oppikofer  
31 2009; Santana et al. 2012), and the definition of potentially movable rock masses (Lato et al., 2009).

32

## 2.2 Description of the proposed methodology

The work presented in this paper includes mainly the two following procedures for:

- (1) The calculation of the PRSD, from small to big rock mass volumes showing high to low susceptibility to failure respectively. This is achieved by the detection of kinematically unstable surfaces on a DEM and on orthophotos, and calculation of the rock mass volumes resting on them.
- (2) The assessment of the IBSD on the slope face, by calculation of the volume of the prisms which are formed by the intersection of the existing discontinuity sets, based on data obtained by analysis of a DEM.

The necessary data for the application of the proposed procedure are a DEM and orthophotos of the study site. Especially for the second procedure a high resolution DEM is needed as for example those acquired by TLS point clouds.

Both procedures need as a prerequisite the identification of the main discontinuity sets. This is also made using the TLS point cloud and the COLTOP3D technique (Jaboyedoff et al., 2004, 2007, 2009; Derron et al., 2005). COLTOP3D is a tool allowing the elaboration of large point clouds and large regular grids of DEM. It permits to visualize the orientation of each discontinuity set by a unique colour, according to the dip direction and the dip of each point of the point cloud, after automatic attribution of a normal vector to it (Metzger et al., 2009). This facilitates the visual identification of discontinuity sets. Additionally, their properties may be evaluated by selecting a representative sample of points from the point cloud that correspond to each set and, then, by assessing statistically their average dip and dip direction.

Having identified the principal discontinuity sets for the study site, the determination of the potential failure mechanisms and of the discontinuity set(s) that contribute to the rockfall detachment is feasible. This is realised through kinematic analysis tests, which should be adjusted to the potential failure mechanisms (i.e. plane or wedge failure or toppling), according to the discontinuity network at each study site. For each specific failure mechanism, the respective conditions according to Markland (1972) and Hoek and Bray (1981) will define which discontinuities are unfavourable, depending on their average dip direction and dip with respect to the slope orientation and angle.

## 2.3 Calculation of the PRSD

The application of the first procedure involves the detection of the Potential Rockfall Size Distribution PRSD on the DEM. The unstable volumes are defined as those rock masses resting on joints that do not meet the stability criteria (Jaboyedoff et al., 2009; Derron et al., 2005). The method consists in the following steps:

Step 1: Using a DEM in raster format, we check compliance with the kinematic criteria for the stability of slopes described at Markland (1972) and Hoek and Bray (1981) at every cell of the raster to define whether

1 a given discontinuity is unfavourable or not. A discontinuity is unfavourable when (a) the joint dip  
2 direction and the slope orientation differ less than 20 degrees; (b) the joint dip angle is bigger than the  
3 friction angle and (c) the joint dip angle is smaller than the slope face angle. For step (b), the friction angle  
4 value depends on the rock joint characteristics and the infill material if any. For unfilled joints in granitic  
5 rock and volumes without any sign of displacement Gates et al. (2005) used the peak friction angle of the  
6 joints. Instead Di Luzio et al. (2013) adopted the residual friction angle in the case of a generic weathered  
7 joint surface filled with soft material. Further indications on the calculation of the shear strength of the rock  
8 joints involving the friction angle are given by Barton (2013) and Grasselli (2001).

9 Figure 1(i) describes the application of the kinematic criteria for a given slope, in every cell of the DEM  
10 raster. It is assumed that all joints are present in every cell. When two potentially unstable cells are  
11 contiguous, it is assumed that they form part of the same removable rock mass (Figure 1(ii)). The detected  
12 potentially unstable surfaces are overlaid on orthophotos for their visual validation. Additionally, the  
13 observation of the orthophotos facilitates the detection of smaller surfaces, if any, inside the previous ones,  
14 which stick out from the topographical relief and correspond to smaller potentially unstable surfaces.

15 Having identified the potential unstable cells and surfaces, the volumes of the corresponding removable  
16 rock masses should be obtained. To assess the total volume of the removable rock mass firstly the area of  
17 the unstable slope face, A, is calculated from the area of unstable cell(s),  $A_{\text{cells}}$  (Equation 1).  $A_{\text{cells}}$  is obtained  
18 using ArcGis utilities.

$$19 \quad A = \frac{A_{\text{cells}}}{\cos\alpha} \quad (1)$$

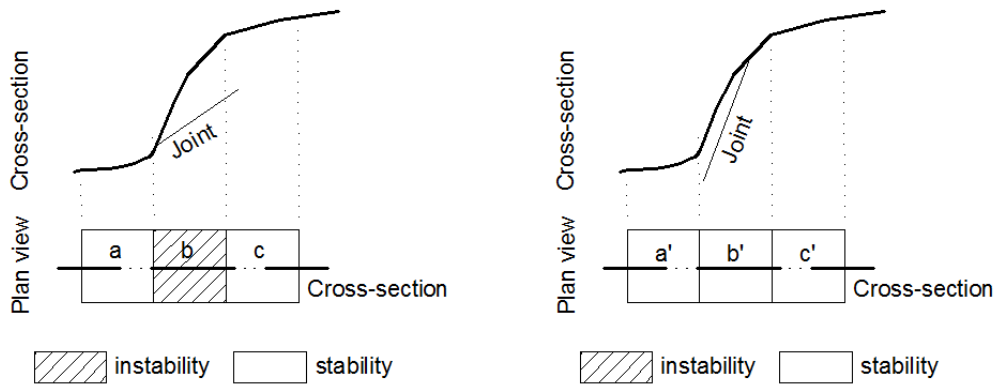
20 Where:

21 A: area of the removable rock mass

22  $A_{\text{cells}}$ : area of the unstable(s) cell(s)

23  $\alpha$ : slope dip angle (average value over the area A)

24



CASE I - pixel "b" is unstable according to the Markland kinematical test

- dip direction joint- dip direction slope < 20°
- and
- joint dip angle < slope face angle

1

CASE II - pixel "b'" is stable according to the Markland kinematical test

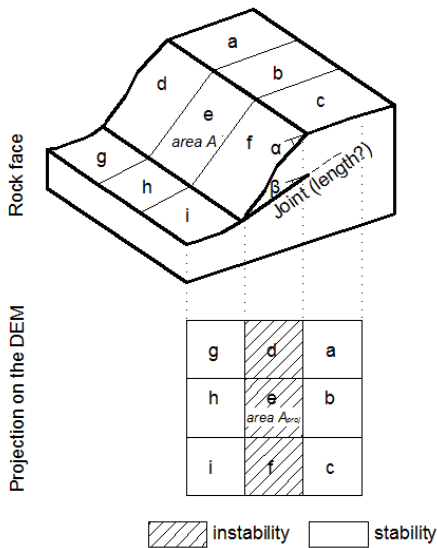
- dip direction joint-dip direction slope > 20°
- or
- joint dip angle > slope face angle

2

**Fig. 1(i)** Application of the kinematic criteria to a given slope (cross section), in every cell of the DEM raster (plan view) on the condition that the joint dip angle is greater than the friction angle.

3

4



5

6

**Fig. 1(ii)** The rock face and its projection on the DEM raster. Unions of contiguous cells are assumed to indicate continuous removable rock masses.

7

8

Step 2: Besides the area of the slope face, the length of the unfavourable joint is required for the calculation of the removable rock mass (Figure 1(ii)). In most cases, this information is not available. If the

9

10

1 persistence of the unstable joints is to be considered infinite, this would describe an extremely conservative  
2 scenario and in most cases not realistic. In the same figure, that would be the case of considering unstable  
3 all three cells “a, b, and c”.

4 For intensely fractured rock masses, the unfavourable discontinuities are usually intersected by others at  
5 relatively short distances from the slope face, defining smaller potentially unstable rock masses. Thus, a  
6 relation between the volume and the joint length was established, which is based on two alternative  
7 considerations: either equivalent cubic volumes are assumed, with all edges equal, or prismatic volumes  
8 where the persistence’s length is half of the height in the previous case. Scar volumes were assumed to be  
9 prismatic. Palmstrom (2005) indicated that for angles of 60° or more between the prism base and height,  
10 the inaccuracy imposed by a simplified measurement that considers all angles of the prism 90° is limited.  
11 This is also valid for the study area as explained in Section 3.

12 According to Hantz (2011), in a general formulation, the relationship between the volume V and the length  
13 L of the fallen compartments depends on the internal structure of the rock wall and it may be written:

$$14 \quad V = kL^3 \quad (2)$$

15 where

16 k: shape coefficient (1 for unknown volumes)

17  
18 Assuming an equivalent cubic shape, the equivalent edge is equal to  $L = A^{0.5}$  and the falling compartments,  
19 corresponding here to potentially unstable rockfall masses, can be calculated by:

$$20 \quad V \approx A^{3/2} \quad (3)$$

21 Where

22 V: the volume of the potentially removable rock mass

23 A: the area of the potentially removable rock mass

24  
25 Accordingly for equivalent prismatic volumes with length L of the joint equal to half of the height of the  
26 afore-mentioned cubic volumes, the volumes can be calculated as:

$$27 \quad V \approx 0.5 A^{3/2} \quad (4)$$

28  
29  
30 The afore-mentioned assumptions describe very conservative scenarios which yield very big volumes. The  
31 presence and intersection of persistent joints that kinematically permit the detachment of rock masses from  
32 the slope face in every cell of the DEM in reality has a very low probability. This is why these volumes  
33 correspond to rare events with low susceptibility of failure.

34 The proposed methodology takes into consideration rockfalls resulting from stepped-path failures. Stepped-  
35 path failures are represented on the DEM when adjacent cells are affected by joints of the same set but that  
36 are situated at different levels instead of a single one.



1 Furthermore it applies to rock mass volumes containing several discontinuity sets. For slopes with one  
2 predominant and continuous discontinuity set and with scarcity of discontinuities intersecting it, large  
3 volumes of greater depth/surface ratio than the equivalent cubic or prismatic volumes that are assumed here  
4 can be formed, even for small slope faces, as for example the typical translational landslides developing on  
5 stratification surfaces (Cruden and Hungr, 1986).  
6

## 7 2.4 Calculation of the IBSD

8 For the second procedure, the point cloud DEM obtained by TLS is used to calculate the In situ Block Size  
9 Distribution IBSD. We make the basic assumption that the in-situ blocks are formed by the intersection of  
10 the discontinuities which are present at the slope and their volume depends on the spacing of the latter, or in  
11 other terms, on the distance between two successive discontinuities of the same set. The intersection of the  
12 discontinuities has to be investigated in order to determine the shape of the in-situ volumes. This can be  
13 realized by direct field observations on the study site in combination with visual inspection of the point  
14 cloud on COLTOP3D.

15 The rock blocks are assumed to be bounded by the existing discontinuities as they intersect each other.  
16 These intersections leading to the formation of rock blocks have to be identified. All sets that produce such  
17 intersections are taken into consideration, irrespectively of whether the blocks are kinematically  
18 unfavourable as in the previous step.

19 For every discontinuity set that contributes to the formation of volumes, the points belonging to it are  
20 isolated from the rest of the point cloud. The points which on visual criterion are detected to belong to the  
21 same surface of the slope are grouped and a plane is automatically fitted to them using the software  
22 Polyworks. This is repeated separately for all the surfaces within each set. During the fitting of planes,  
23 neighbouring points that exceed a maximum in-between distance and angular deviation are filtered out. The  
24 calibration of the used thresholds is made by observations of the photos of the area, so as to get realistic  
25 planes fitted.

26 Then to assess the average spacing for each discontinuity set, Polyworks utilities were used to measure  
27 manually, one by one for all planes, the perpendicular distance from an origin point on a plane near its  
28 centre, to its neighbouring plane, at a representative sample of the cliff. Two extreme assumptions are made  
29 for the calculation of the average spacing: a) discontinuity sets are of infinite persistence, thus having the  
30 minimum value of spacing between them, which is a theoretical case, or b) discontinuity sets are of finite  
31 persistence having an average spacing equal to the average perpendicular distance between the quasi-  
32 parallel surfaces measured on the DEM and considering only the visible trace length. The average spacing  
33 at a representative area of the cliff for the two assumptions on the discontinuity persistence is calculated  
34 according to Jaboyedoff (1996 and 2001) from the traces of the joints for every discontinuity set, as shown

1 in Figure 2. The software Mattercliff (Délèze et al., 2003) was used. For the assumption (a) the average  
 2 spacing is the smallest because the joints are of infinite persistence so inside the sampling window the  
 3 number of intersections with a scanline is the greatest (Figure 2). For the same sampling window and for  
 4 the assumption (b) only the visible trace length of the discontinuities at each plane is considered and the  
 5 number of intersections with a scanline is smaller.

6 The distribution of spacing massively over the slope cliff can be given by a negative exponential  
 7 distribution as suggested by various researchers (Krishna et al., 2009; Priest and Hudson, 1981; Wallis and  
 8 King, 1981; and Kulatilake et al., 1995), with the following probability density function:

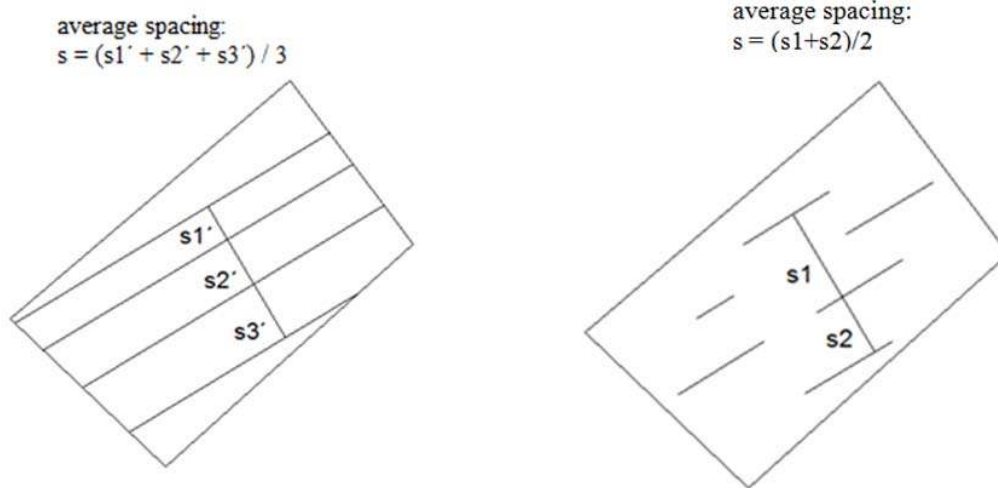
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$$10 \quad P(x) = \frac{1}{s} e^{-\frac{x}{s}}, \quad x \geq 0 \quad (5)$$

11

12  $s$ : mean discontinuity spacing

13



14

15 **Fig. 2** Indicative calculation of the average spacing considering discontinuities of infinite (case a – left)  
 16 and discontinuities of finite persistence (case b – right)

17

18

19 IBSD can then be assessed in function of the discontinuity spacings for the selected intersecting sets. For  
 20 quasi-regular parallelepipeds with edges equal to the average spacing and infinite discontinuities, a regular  
 21 parallelepiped can be considered for the shape of the blocks. For finite discontinuities, an equivalent quasi-  
 22 regular parallelepiped can be also considered, with edges equal to the respective average spacing. So, these  
 23 volumes can be approximated by equivalent prismatic volumes by (Kim et al., 2007):

24

1 
$$Vo = s_{j1} * s_{j2} * s_{j3} \tag{6}$$

2

3  $s_{j1}, s_{j2}, s_{j3}$ : discontinuity spacing of the bounding intersecting discontinuity sets

4

5 The volume variation due to the variation of spacings over the slope is probabilistically accounted for, with  
6 a Monte Carlo simulation where spacings follow the negative exponential distribution. These results yield a  
7 probabilistic relation for the IBSD for every intersection of discontinuities and infinite or finite persistence  
8 assumptions.

9

### 10 **3 Application**

11 The proposed procedures are presented through an application example at a selected study-site. It is the  
12 slope situated above the urban area of Santa Coloma, in the country of Andorra, in the Middle Eastern  
13 Pyrenees.

14

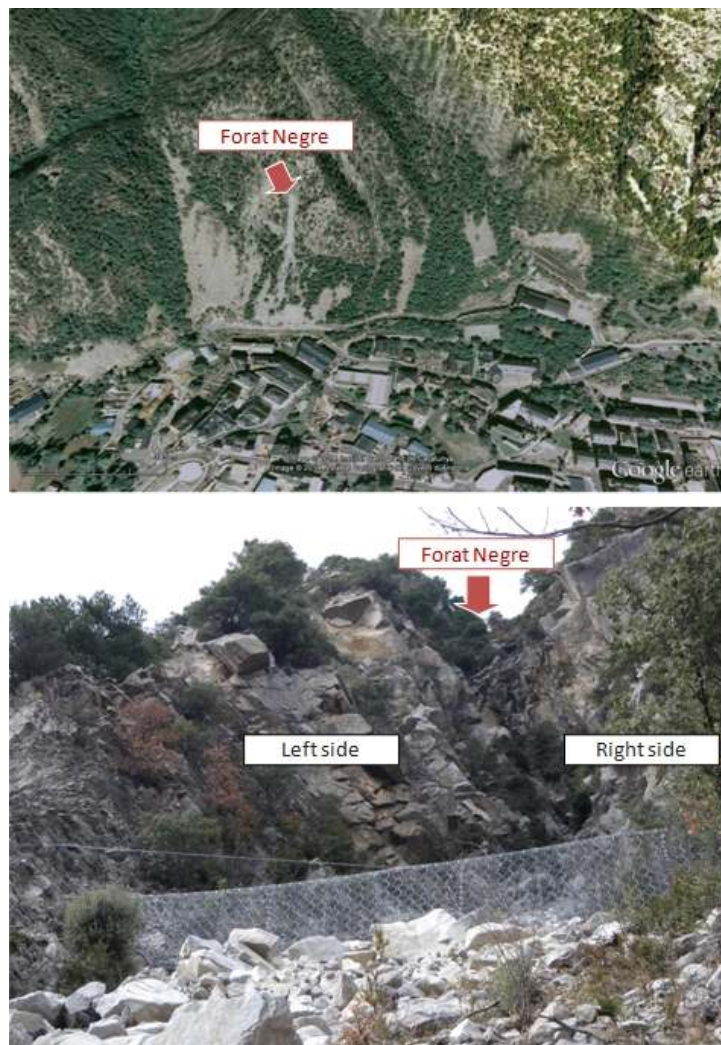
#### 15 **3.1 Description of the study-area**

16 For the wider area, the retreat of the Pleistocene glaciers about 20000 years ago has resulted in a typical U-  
17 shape valley profile. The subsequent occurrence of morphogenetic processes such as decompression and  
18 freeze-thaw cycles has resulted in intense rockfall activity under non-seismic conditions. The slope next to  
19 the valley exceeds the 1000 m and the rock material is basically intensely fractured granodiorite. Its special  
20 interest is ought to the rockfall risk for the buildings which lie at the low part of the slope.

21 In particular we investigate the chute of Forat Negre (Figure 3) where unstable volumes are present at the  
22 left and right side of the chute. During the last decades various rockfall events of magnitude up to some  
23 hundreds of cubic meters occurred and produced blocks up to 30 m<sup>3</sup> reaching and damaging buildings and  
24 injuring people.

25 The wider area is characterized by intense rockfall activity, of approximate annual frequency 0.5  
26 events/year (Moya et al. 2010), with rockfall volumes, varying from a few cubic to several thousand  
27 meters. An inventory of rockfall events for the area was compiled by Copons (2004), including events since  
28 the end of the 1960s. For that period and, strictly, for the investigated slope, the rockfall magnitudes are  
29 limited up to some hundreds of cubic meters. As for example the event of April 2004 of a rockfall of 25 m<sup>3</sup>  
30 resulted in fragments up to 4 m<sup>3</sup>. On April 2008, a rock mass volume of approximately 150 m<sup>3</sup> was  
31 detached from the slope face with the biggest fallen block approximately of 30 m<sup>3</sup>. The latest event was  
32 registered on February 2014, when a mass of approximately 20 m<sup>3</sup> produced various blocks of maximum  
33 size 4.5 m<sup>3</sup>, and a block of 3.50 m<sup>3</sup> reached the urban area and penetrated the wall of a workshop.

1 Nevertheless, higher rockfall magnitudes of the order of 1000 m<sup>3</sup> have been observed at adjacent chutes (at  
2 the Tartera de la Pica on April 1969), implying a potential for higher volumes also for the study-site.  
3 Nowadays, high-energy dissipative steel fences are installed at the bottom of the slope, which at recent  
4 rockfalls were proved very efficient at retaining the majority of blocks. However, failure at impeding the  
5 blocks reaching the buildings has also been observed which was caused by the excessive rotation of the  
6 vertical supports of the nets, thus permitting the blocks to fly over them. Consequently their efficiency  
7 cannot be guaranteed for high magnitude events leading to considerable rotations of the supports and so the  
8 occurrence of the latter should be studied. To this purpose, it is a major issue in the study-site to investigate  
9 the potential of big volume failures as well as the size of the blocks formed by the intersection of  
10 discontinuities on the cliff that will contribute to the formation of the blocks that are probable to reach the  
11 protection barriers.  
12



13

1 **Fig. 3** General view of the Solà d'Andorra above Santa Coloma (up) and close view of the Forat Negre  
2 rockfall sources and chute (down)  
3

4 To obtain accurate topographical data, field work was performed which consisted in capturing  
5 topographical data using a TLS. The used device was an Optech Intelligent Laser Ranging and Imaging  
6 System (OPTECH-ILRIS3D), composed by a transmitter/receiver of infrared laser pulses and a scanning  
7 device. The average scanning distance from the slope was less than 600 m. Using a TLS the topographical  
8 relief is represented by a point cloud based on the distance and orientation of the points from the device,  
9 including the 3D coordinates of each point. Points were obtained every less than 1 cm approximately. More  
10 technical specifications on the use of TLS and the data acquisition can be found at Abellán et al. (2006 and  
11 2009).

12 For the slope face of Forat Negre, a series of scans from two different stations was carried out to avoid  
13 missing points which are not visible from a given station. For one station two scans were needed to cover  
14 the entire zone of interest. Afterwards, the 3 point clouds were superimposed and aligned using the  
15 software POLYWORKS (InnovMetric©) to obtain a final 3D point cloud (Oppikofer et al., 2009).

16 During the laser scanning, objects wholly or partially hidden from the point of view of the scanner were not  
17 captured at the Lidar dataset, resulting in uncertainty about their presence or position in the scene.  
18 Moreover, as vegetation and trees are present in the area, after the removal of the respective points from the  
19 point cloud, the resolution of the DEM was locally affected. Thus a DEM of standard resolution had to be  
20 used for this application.

21 Based on the point cloud a moderate-precision 5 m contour DEM was also produced in ASCII format, with  
22 cell size 1x1 m<sup>2</sup>.

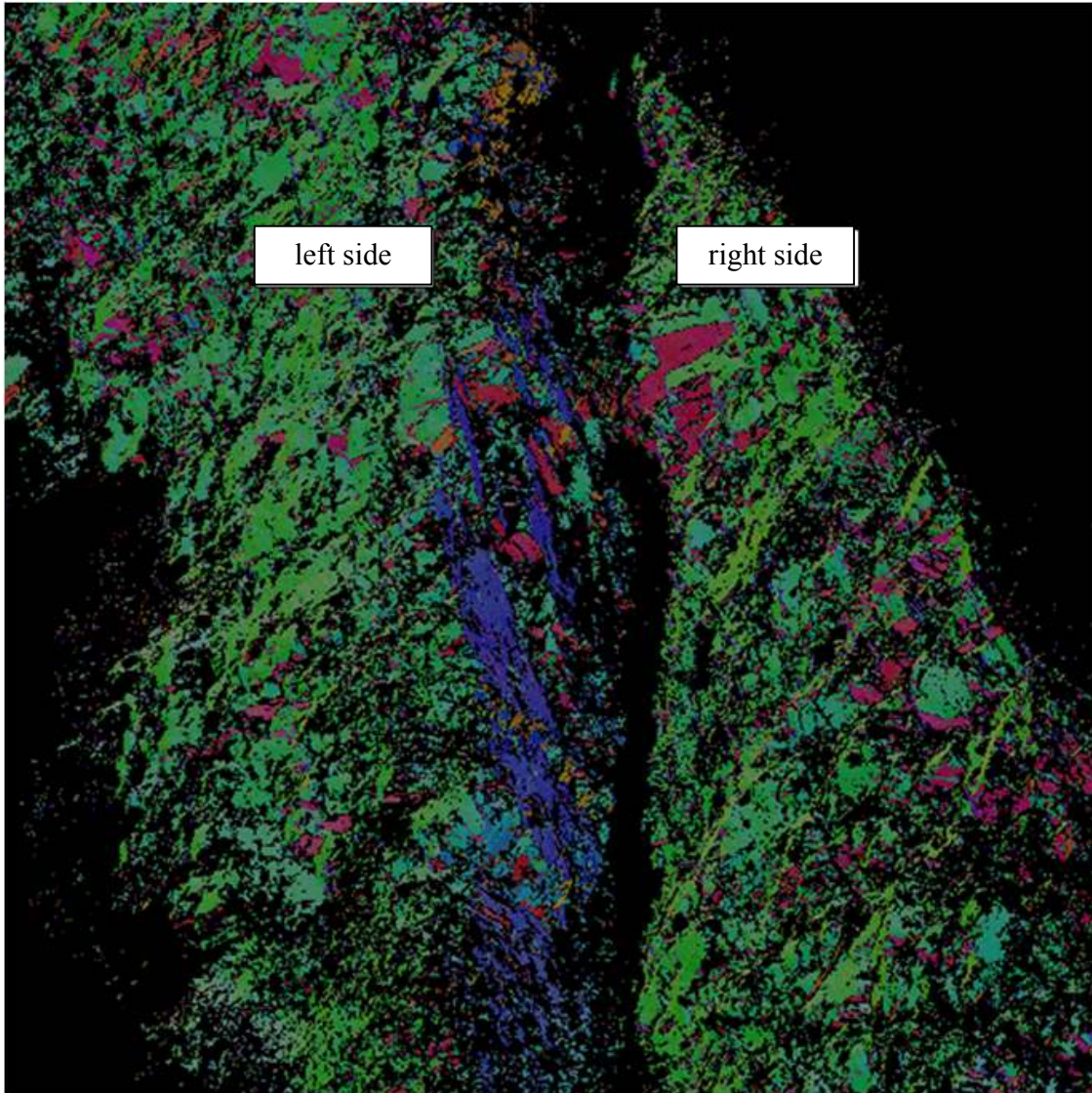
### 24 **3.2 Identification of discontinuity sets and failure mechanisms**

25 The point cloud of the study-area, as represented by COLTOP3D is shown in Figure 4. The characteristics  
26 of every discontinuity set were assessed by calculating the average values of the dip and dip direction for  
27 selected representative subsets.

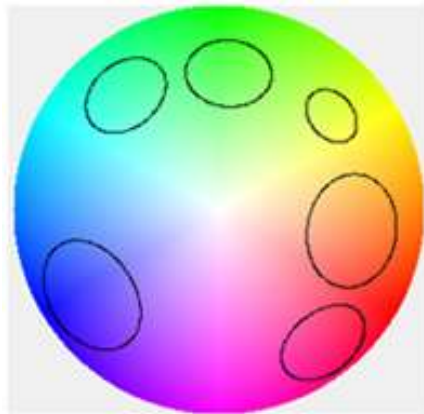
28 For each set, small representative groups of points were manually selected. For simplification their average  
29 dip and dip direction were assumed to be representative for the whole set, with a tolerance to consider their  
30 variation. For the study-area, 6 discontinuity sets were identified (Figure 5). Dip and dip direction for each  
31 set are selected so as the points that do not belong to the set (noise) to be excluded and the points that  
32 apparently belong to it to be included. Validation is made on visual inspection of the point cloud and photos  
33 of the study site. The tolerance value is different for each set. Comparison of the discontinuity sets with  
34 those found by field survey (Copons, 2004), show good convergence of the results. The most frequent are



1 J1 and J2. J3 often co-exists with J2, but due to the significant variation of their dip and dip direction they  
2 are considered separately. J4 and J5 alternate in the formation of unstable volumes intersecting the rest of  
3 the sets. J6 is very scarce over the slope and accordingly the corresponding volumes are few and they are  
4 not taken into account. The most important discontinuity sets J1 to J5 are present along the entire slope.  
5  
6



7  
8 **Fig. 4** Image of the point cloud in COLTOP3D. The 6 principal discontinuity sets are depicted with  
9 different colours (violet, fuchsia, orange, green, light blue, yellow).  
10



Set	Colour	Dip Dir.	Dip	Tolerance
J1	Violet	56	65	20
J2	Fuchsia	322	72	15
J3	Orange	279	56	20
J4	Green	184	57	15
J5	Light blue	141	62	15
J6	Yellow	230	61	15

1

2 **Fig. 5** Stereogram and principal discontinuities sets for the study site

3 Site inspection shows that plane failure is the predominant mechanism in the study site. Assuming sliding  
 4 as the principal mechanism in generating rockfalls, the discontinuity sets J4 and J5 act unfavourably by  
 5 comparison to the slope angle, permitting the detachment of rock volumes. J4 and J5 sets do not intersect  
 6 each other; instead they alternate at the formation of the rock volumes.

7

### 8 **3.3 Potentially unstable rock masses size distribution, PRSD**

9 As indicated by the analysis of the discontinuity sets at the previous section, J4 and J5 are unfavourable  
 10 discontinuity sets that permit the detachment of rockfalls. The slope orientation and angle of the  
 11 topographic surface are compared with the dip direction and dip of these two sets, at every cell of a 1x1 m<sup>2</sup>  
 12 resolution DEM, to produce the raster indicating in which cells failure is kinematically possible. Unions of  
 13 adjacent cells producing large surfaces were also observed.

14 Using ArcMap tools, the obtained surfaces were superimposed on the orthophotos and marked with  
 15 polygons. Additionally, after the observation of the orthophotos, smaller surfaces that stick out from the  
 16 topographical relief and that correspond to separate smaller potentially unstable surfaces were detected  
 17 inside the perimeter of those polygons. The application of the proposed procedure to Forat Negre is shown  
 18 in Figure 6, where the polygons indicate the surfaces where both sets J4 and J5 are unfavourable. Given the  
 19 vicinity of J4 and J5 at the stereogram, the surfaces on the projected DEM where these two sets are present,  
 20 are common in their majority. 47 surfaces were detected in total, of which 9 on the left side and 38 on the  
 21 right (Table 1).

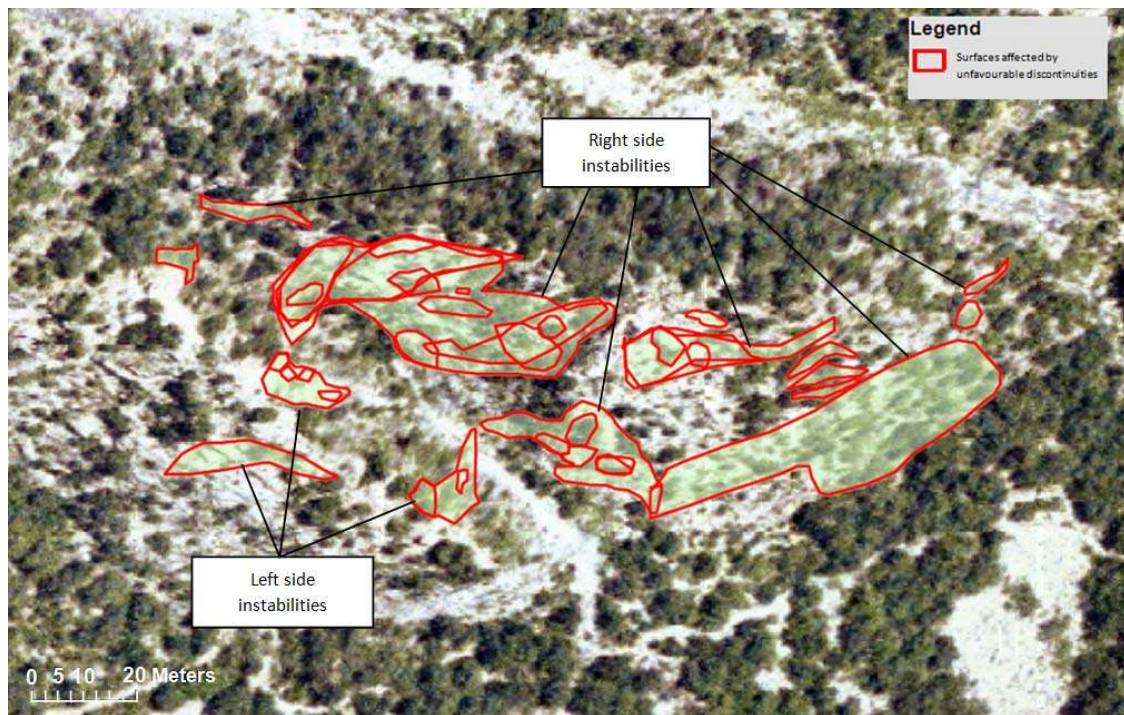
22 The areas of these polygons were calculated as illustrated at the area-frequency diagram of Figure 7. They  
 23 vary from 2 m<sup>2</sup> up to 1361 m<sup>2</sup> the biggest one. As afore-mentioned, big surfaces might correspond to the



1 union of smaller neighbouring surfaces on the two-dimensional DEM. This means that a rockfall with an  
2 area of 1361 m<sup>2</sup> is possible to be released from the slope face as a unique mass or, alternatively, through  
3 small successive failures. The areas of smaller surfaces inside the big ones were as well added separately  
4 into the dataset to build the area-frequency diagram, as it is not known a priori whether smaller or larger  
5 failures will take place.

6 The volume distributions were calculated for cubic and prismatic volumes from Equations (3) and (4). The  
7 cumulative diagrams are shown in Figure 8. The maximum kinematically removable rock masses that were  
8 indicated using this procedure are of the order of 50000 m<sup>3</sup> and 25000 m<sup>3</sup>, for cubic and prismatic volumes  
9 respectively. This order of magnitude complies with the thresholds established for fragmental rockfalls (see  
10 Section 1). They represent big volumes which have never been previously observed in the study-site, but  
11 are kinematically possible. Table 1 shows the results of this analysis differentiating between the left and the  
12 right side of the chute. The most and largest instabilities were detected on the right side as also depicted in  
13 Figure 6, due to the slope's orientation.

14

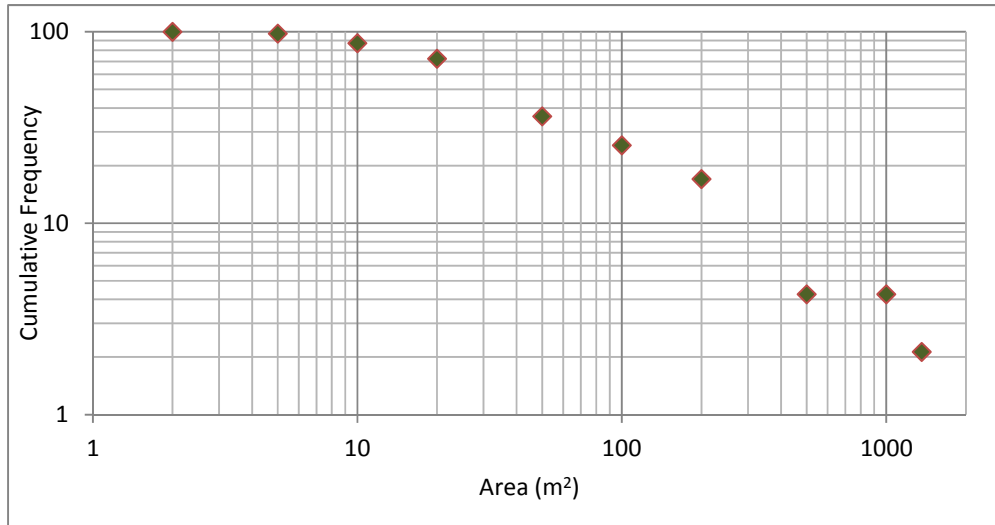


15  
16

17 **Fig. 6** The surfaces where the discontinuity sets J4 and J5 are unfavourable permitting the detachment of  
18 rockfall mass from the cliff face.

19

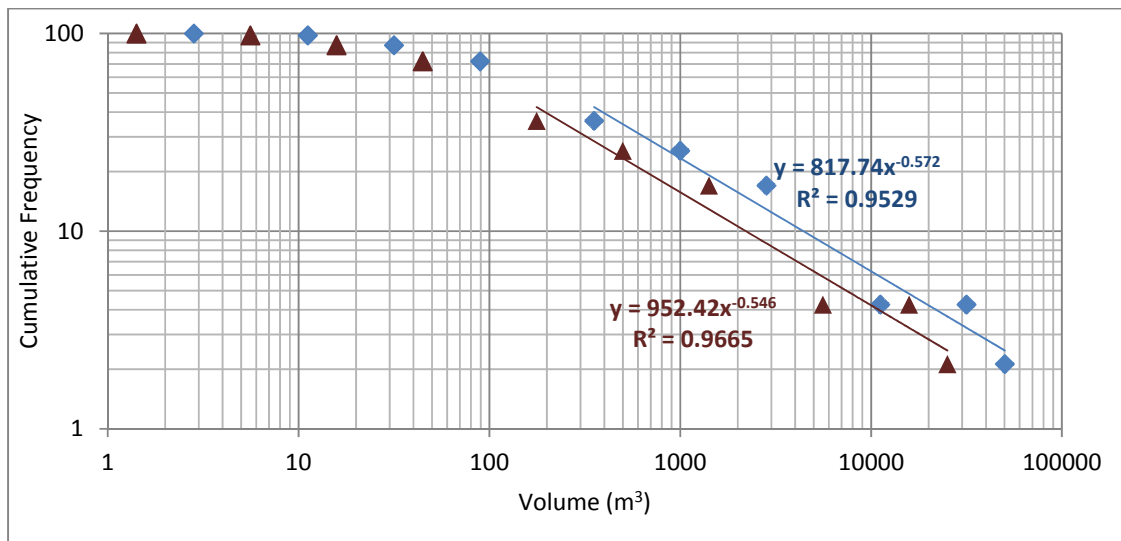




1

2 **Fig. 7** Size distribution (cumulative frequency) of basal areas of potentially unstable rock masses

3



4

5

6 **Fig. 8** PRSD –Potentially unstable rock masses size distribution for cubic (rhombus) and prismatic  
7 (triangles) shape . Power-law fitting for volumes corresponding to volumes equal or greater than 100 m³.

8

9 **Table 1.** Size distribution (cumulative frequency) for the left and right side of the chute

Area (m2)	Volume - cube (m3)	Volume - prismatic (m3)	Cum. frequency - left side	Cum. frequency - right side
0-2	0-3	0-1	9	38
2-5	3-11	1-6	9	37

5-10	11-32	6-16	9	32
10-20	32-89	16-45	5	29
20-50	89-354	45-177	5	12
50-100	354-1000	177-500	5	7
100-200	1000-2828	500-1414	5	3
200-500	2828-11180	1414-5590	1	1
500-1000	11180-31623	5590-15811	0	2
1000-1361	31623-50210	15811-25105	0	1

1

2 As aforementioned correlating the rockfall size distribution with the frequency-magnitude relation was out  
3 of the scope of this paper. However, to check the results, the volume distribution of Figure 8 was compared  
4 against the volume of real events in the study-site and their relative frequency. The observed events of 25  
5 m<sup>3</sup> are approximately two times more frequent than those of 150 m<sup>3</sup> (Corominas and Mavrouli, 2013).  
6 Using the data of Figure 8 for cubic and prismatic volumes, these ratios are 1.5 and 1.2 respectively. This  
7 means that in reality big volumes are less frequent than smaller ones in comparison with the calculated  
8 statistical ratio.

9 At the diagrams shown in Figure 7 and Figure 8, the frequency of small volumes (i.e. smaller than 50 m<sup>3</sup>) is  
10 underestimated as the visual observation of the orthophotos does not permit the detection of all volumes  
11 sticking out from the topographical relief, or because rock masses of big areas and volumes do not  
12 necessarily fail as a single event. So to assess the power-law exponent for big rockfalls volumes, we  
13 considered volumes greater than 100 m<sup>3</sup>. It was observed that big volumes follow a power-law with an  
14 approximate exponent of -0.5. This exponent is different than the one indicated by Santana et al. (2012) for  
15 the same study-site, where it was found that volumes corresponding to rockfall scars are well fitted by a  
16 power-law with an exponent of -0.9 approximately. The value of -0.9 yields smaller volumes that mostly  
17 approximate the observed small and intermediate events, without taking into account a potential stepped-  
18 path failure. Instead the exponent -0.5 corresponds to bigger volumes and has been assessed taking stepped-  
19 path failures into consideration.

20

### 21 **3.4 In-situ rock block size distribution, IBSD**

22 The second procedure also requires the discontinuity sets that were previously identified for the calculation  
23 of the PRSD. At first point, we defined the way that the discontinuities intersect each other on the cliff and  
24 contribute to the formation of the in-situ blocks. An example is shown in Figure 9. Close observation of the  
25 point cloud indicates that the potentially unstable rockfall volumes are formed by the intersection of the  
26 three following combinations of discontinuity sets (Figure 10):

27

- Volumes V1: J1+J2+J4

1 • Volumes V2: J1+J2+J5

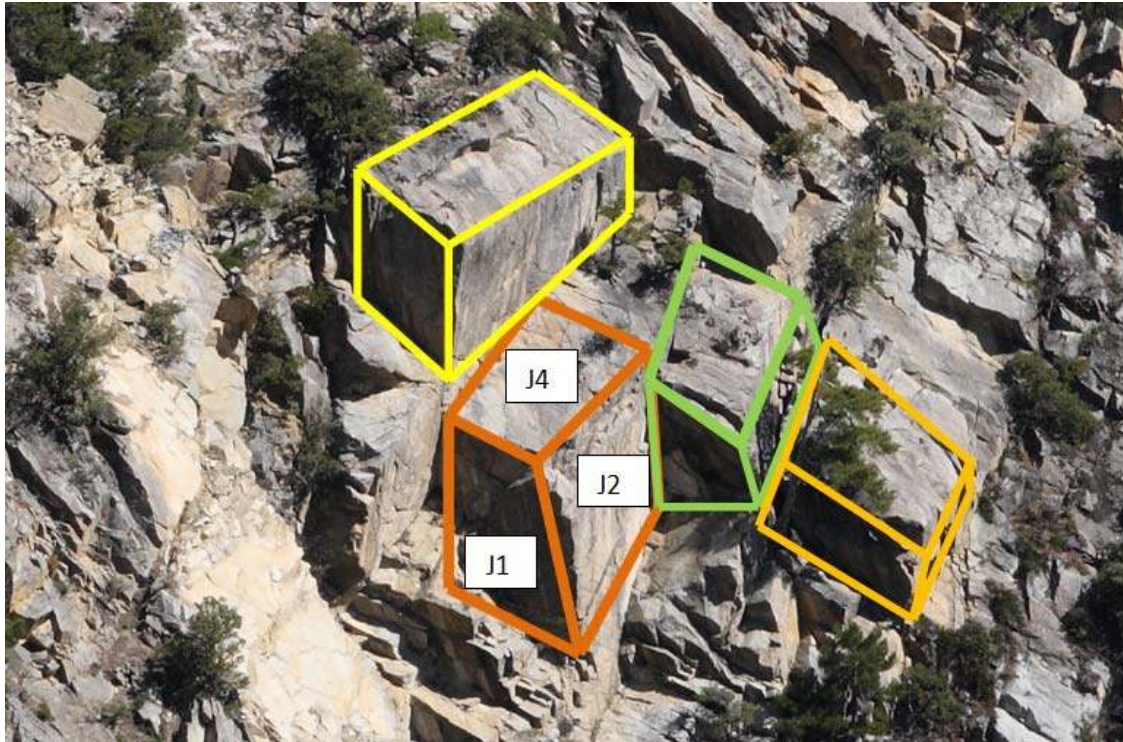
2 • Volumes V3: J1+J3+J5

3 J4 and J5 form the sliding basal surface of the block. The volumes of type V1 and V2 are the most frequent.

4 Volumes V1 are mainly present on the right side of the chute while volumes V2 on both sides. The volumes

5 V3 are very scarce in the study site.

6

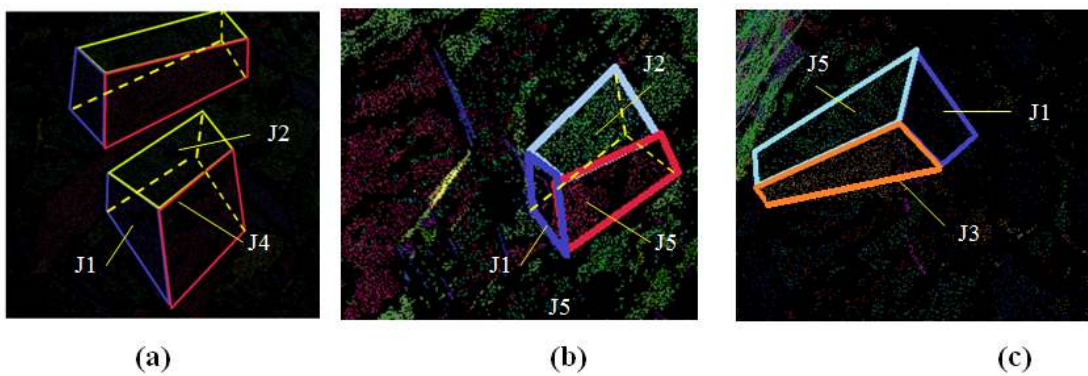


7

8 **Fig. 9** Example of in-situ rock blocks in the study site (J1, J2 and J4 are discontinuity sets )

9

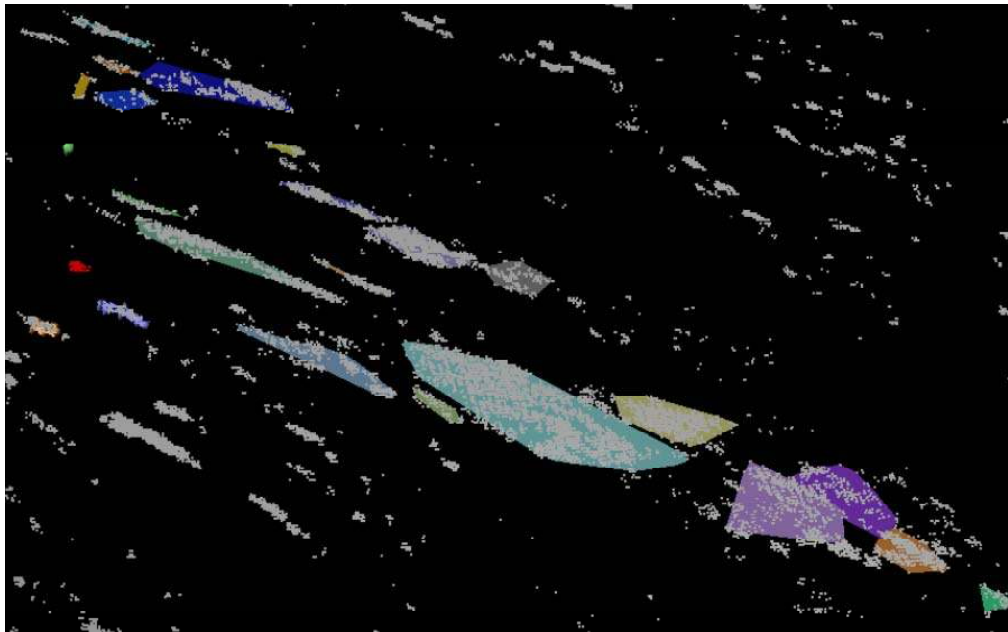
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11

1 **Fig. 10** Intersection of different discontinuity sets for the formation of unstable volumes: (a) volumes V1,  
2 (b) volumes V2, (c) volumes V3

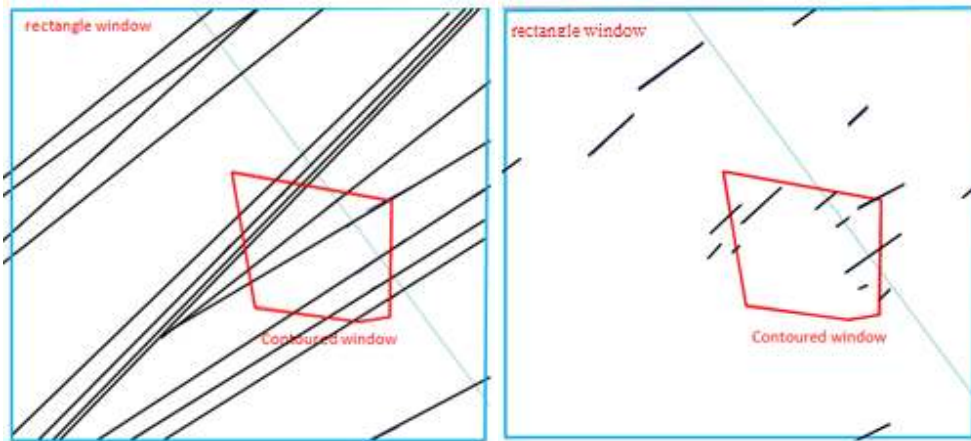
3  
4 The points of the TLS point cloud were grouped into discontinuity sets and exported to Polyworks. 6  
5 groups of points were created, as many as the discontinuity sets. Then, separately for every group we  
6 detected visually the points corresponding to the exposed surfaces on the cliff and we fitted automatically a  
7 plane to each exposed surface (segment). The automatic fitting of a plane to the points belonging to the  
8 same segment was made by regression: once the current segment reached a predefined number of points (6)  
9 an orthogonal regression plane was fitted to it. To filter out points not belonging to the segment, the  
10 normal vector of a given candidate point was checked with reference to the normal vectors of all points  
11 included in a sphere with centre the candidate point and 1 m diameter. Candidate points with a normal  
12 vector deviating more than  $45^\circ$  with reference to their neighbouring points were filtered out. This angle was  
13 chosen to permit a certain undulation or rugosity of the surfaces. Figure 11 shows indicatively the fitted  
14 planes for the discontinuity set J1 at Polyworks.



16  
17 **Fig. 11** Fitting of planes for the points cloud of the discontinuity set J1

18  
19 The planes were then exported as polygons from Polyworks to Autocad v.10; the trace of all planes on an  
20 approximately perpendicular surface to them in the direction of their dip, were drawn separately for each  
21 set (one perpendicular surface was visually approximated here for all planes in the same set). Once the  
22 traces of the planes were defined, a representative window was selected for the characterisation of each set.

1 Sampling windows (Priest and Hudson 1981) were used to this purpose. The sample windows were  
 2 selected to be representative of the density of joints compared with those observed in-situ. The selection of  
 3 big sampling windows may incorporate errors related to not detected planes, thus small but representative  
 4 ones are preferred. An indicative sample window for the discontinuity set J3 is shown in Figure 12.  
 5



6  
 7 **Fig. 12** Window sampling for the calculation of spacing for the discontinuity J3 considering joint of infinite  
 8 persistence joints (case a –left) and (b) joints of finite persistence (case b – right)  
 9

10 The results for the average spacing, for infinite and finite persistence of the discontinuities are summarized  
 11 at Table 2. In most cases, the results indicate approximately half spacing when fully persistent joints are  
 12 considered rather than discontinuous. The discontinuities J2 and J4 for the case of finite persistence have  
 13 higher values in comparison with the rest.

14  
 15  
 16

**Table 2** Average spacing of discontinuity sets from the sampling window

Discontinuity set	Spacing assuming discontinuities of infinite persistence (theoretical case)	Spacing assuming discontinuities of finite persistence
	(m)	(m)
J1	1.6	3.7
J2	4.9	11.5
J3	0.7	1.6
J4	2.4	9.8
J5	1.2	3.6

17  
 18

1 **Table 3** Average in-situ rock block volumes (m<sup>3</sup>)

Intersecting discontinuity sets	Volumes for discontinuities of infinite persistence	Volumes for discontinuities of finite persistence
V1: J1+J2+J4	18	422
V2: J1+J2+J5	9	162
V3: J1+J3+J5	1	20

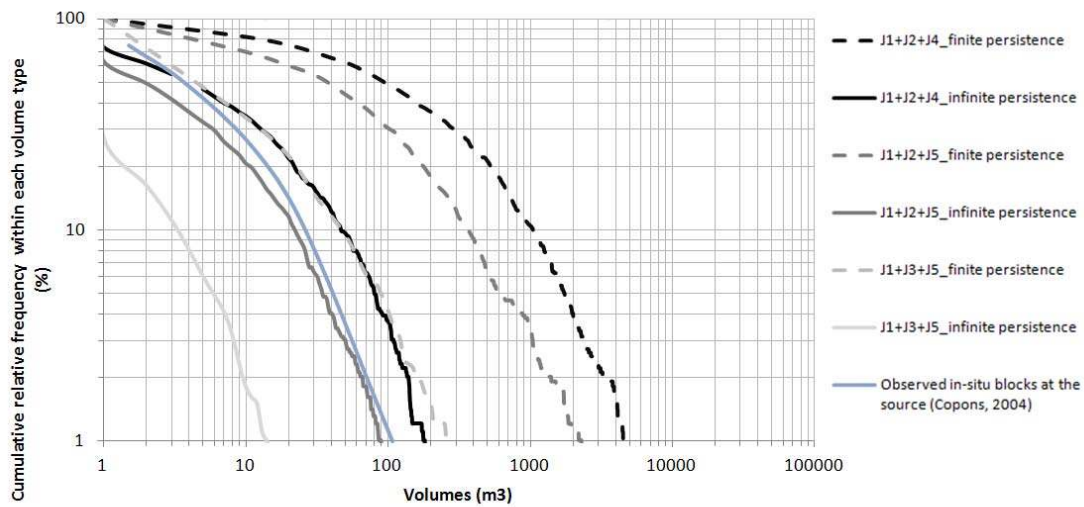
2

3 As the prisms angles are lower than 60°, according to Palmstrom (2005) Equation (6) can be directly  
 4 applied using the average spacings of Table 2 as explained in section 2.4 and assuming that they follow the  
 5 negative exponential distribution of Equation (5). Table 3 shows the average in-situ rock block volumes  
 6 calculated by a Monte Carlo simulation, for 1000 samples for all the three discontinuity intersections  
 7 (volume types V1 to V3), for the minimum theoretical spacings for joints of infinite persistence and of  
 8 finite persistence. The standard deviation was also calculated to be 44, 40 and 3 m<sup>3</sup> for V1, V2 and V3 and  
 9 discontinuities of infinite persistence and 1135, 436 and 56 m<sup>3</sup> for discontinuities of finite persistence  
 10 respectively. Such values of the standard deviation indicate high spread of the data. The values of Table 3  
 11 also indicate the most expected sizes of the rock blocks for the study site on the theoretical condition that  
 12 fractures take place exclusively along the pre-existent discontinuities and no new fractures are created. The  
 13 volume of 422 m<sup>3</sup> is not a representative value for the studied chute as no fragments of that size have been  
 14 registered so far in the study-site. This indicates that the values of spacings for discontinuities of finite  
 15 persistence provide overestimated volumes, which is conservative.

16 Figure 13, based on the same Monte Carlo simulation, yields the IBSD for every intersection of  
 17 discontinuities, for infinite or finite persistence assumptions. It is emphasised that the spatial distribution of  
 18 all intersections of volumes cannot be calculated as the sum of the curves of Figure 13.

19





1

2 **Fig. 13** IBSD for the average spacing of three intersections of discontinuities considering discontinuities  
 3 of finite and of infinite persistence (volumes V1: J1+J2+J4, V2: J1+J2+J5, V3: J1+J3+J5) and the observed  
 4 IBSD (Copons, 2004)

5

6 The maximum calculated values of the in-situ volumes are of the order of some thousands of cubic meters.  
 7 The biggest volumes are defined by the combination of the J1, J2, J4 joint sets (volumes V1) considering  
 8 finite persistence, thus the presence of rock bridges. For V1, 10% is greater than 1000m<sup>3</sup>. Volumes V2  
 9 (J1+J2+J5) and of finite persistence may also give blocks of the same order of magnitude (4.5% of the  
 10 volumes are greater than 1000 m<sup>3</sup>). Volumes V3 for finite persistence, as well as V1 for infinite persistence  
 11 give rock blocks of the order of some hundreds of cubic meters (3% exceeds 100 m<sup>3</sup>) while V2 and V3 for  
 12 infinite persistence are of some decades of cubic meters. For the study-site and especially for the chute of  
 13 Forat Negre, the largest registered block reaching the foot of the rockfall cone has been 46 m<sup>3</sup>, which is of  
 14 the order of magnitude of the in-situ block volumes calculated for discontinuities of infinite persistence.

#### 15 **4 Discussion**

16 In Forat Negre, the maximum in-situ observed block volume at the source area (on the rocky slope) is 184  
 17 m<sup>3</sup> and at the wider area is 270 m<sup>3</sup> (Copons, 2004). The calculated volumes which are greater than 184 m<sup>3</sup>  
 18 correspond to percentages lower than 50% (approximately 40% for V1, 25% for V2 and 1.5% for V3, for  
 19 finite discontinuities and less than 2% for V1 for infinite discontinuities).

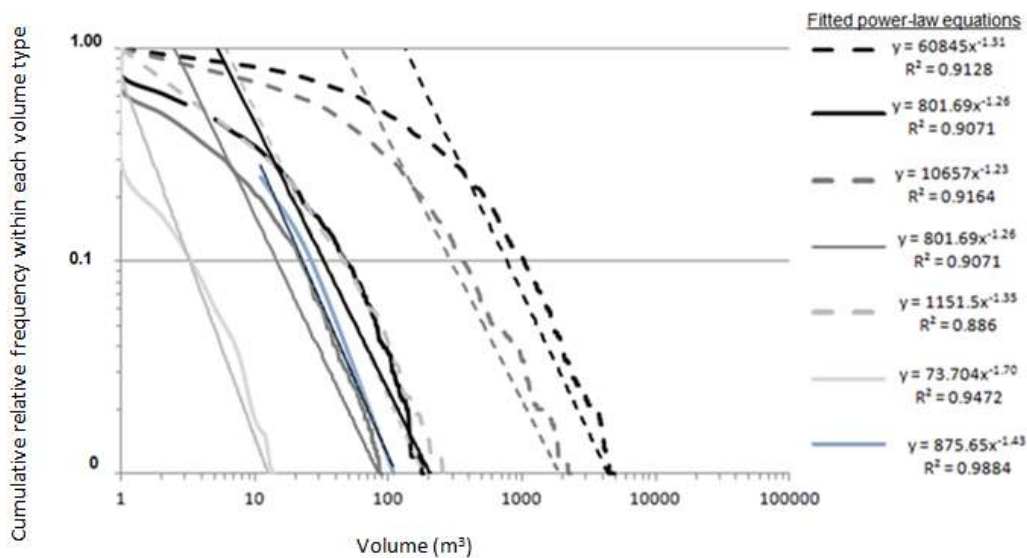
20 For the two assumed persistences and for 1% cumulative relative frequency there is a difference of one or  
 21 two orders of magnitude in the volumes: for V1 it is reduced from 4500 m<sup>3</sup> to 200 m<sup>3</sup> (23 times smaller for  
 22 infinite persistence), for V2 from 2100 m<sup>3</sup> to 90 m<sup>3</sup> (23 times smaller) and for V3 from 250 m<sup>3</sup> to 15 m<sup>3</sup>

1 approximately (17 times smaller). This shows the importance of the persistence and the formation of rock  
 2 bridges in the rock mass for the size distribution of rock blocks.

3 To check the consistency of these results with real observations, we plotted a curve with the field data for  
 4 the observed in-situ blocks measured by Copons (2004) in the source area, as seen in Figures 13 and 14.  
 5 Those volumes have been defined on the slope face by volumetric analysis of the blocks bounded by the  
 6 existing discontinuity sets, by direct measurement of the nearly detached blocks, and by estimation of their  
 7 size from photos. The plotted curve is better approximated by the case of discontinuities of infinite  
 8 persistence (Figure 14). This leads to the conclusion that for the study-site which is intensely fractured,  
 9 evaluating the persistence only by the visible trace length of the discontinuities is a very conservative  
 10 assumption. Instead the size distribution of the in-situ blocks is better approximated in the theoretical case  
 11 of infinite discontinuities, although in some cases this may lead to underestimation of big volumes. It can  
 12 be deduced that discontinuities have a finite persistence which is high and close to the theoretical case of  
 13 infinite persistence, although not the same.

14 Power-law distributions were fitted to the data, which were all found to have an exponent of -1.3  
 15 approximately, with the exception of the volumes V3 for infinite discontinuities, which are fitted by a  
 16 power law with an exponent -1.70. Field data also were well fitted by a power-law distribution with an  
 17 exponent of -1.4 for volumes higher than 11 m<sup>3</sup> (for smaller volumes the fitting was not satisfactory),  
 18 which is a good approximation of the results. Fig. 14 indicates that the power-laws, despite their high r<sup>2</sup>  
 19 coefficient, fit the right part of the curves but for the left part they fail to describe satisfactorily the relative  
 20 frequency. The similarity of these exponents indicates that at least some parts of these curves have similar  
 21 shape. This is an evidence of repetition at the rock block patterns, possibly related to the process of the  
 22 structural formation of the slope.

23



24



1 **Fig. 14** Power-law fitting of the calculated IBSD (volumes V1: J1+J2+J4, V2: J1+J2+J5, V3: J1+J3+J5)  
2 and of the observed IBSD (Copons, 2004)  
3  
4

5 The probabilistic calculation of the rock block volumes was based on the assumption of a negative  
6 exponential distribution, however it still remains to investigate whether there is a physical limit of spacing  
7 that would imply the truncation of the exponential distribution, and thus impeding the formation of blocks  
8 above a certain size.

9 In some cases, during the impact with the ground there is the possibility of segmentation of the detached  
10 rockfall mass not only along the pre-existing planes of the discontinuity sets but also by propagation and  
11 coalescence of the discontinuities into the rock bridges or by the development of new cracks in the intact  
12 part of the rock. The blocks deposited downslope in the study area might be the result of all these  
13 segmentation processes. As the segmentation along rock bridges or new cracks has not been investigated  
14 for the study area, the IBSD cannot be compared with the curve of blocks deposited downslope, also  
15 measured by Copons (2004).  
16

## 17 **5. Conclusions**

18 In this paper an alternative methodology was presented for:

- 19 (1) The calculation of the potentially unstable rock masses size distribution PRSD that refers to big  
20 volumes corresponding to rare events with low susceptibility of failure, by detection of  
21 kinematically unstable surfaces on a DEM and on orthophotos.
- 22 (2) The assessment of the in-situ rock blocks size IBSD distribution on the slope face, by calculation  
23 of the equivalent volume of the prisms which are formed by the intersection of the existing  
24 discontinuity sets.

25 A high-resolution DEM is needed, especially for (2). Both procedures are independent from the existence  
26 of past data and may be used to overcome limitations related to access restrictions and high field work  
27 costs. Further advantages of the procedures are that they are simple, they need few input data and they can  
28 provide results at massive scale.

29 The obtained information can provide some clues for the rockfall magnitude frequency relation and the size  
30 distribution of the fallen blocks during the process of rockfall hazard and risk assessment, especially when  
31 it comes to their quantification; however this has not been investigated here.

32 The first proposed procedure is based on assumptions describing a conservative scenario of very low  
33 probability, such as that (a) the potential rockfall mass is detached entirely at a single rockfall event,  
34 without taking into account that smaller successive failures are possible instead, (b) all discontinuity sets  
35 are present everywhere in the slope - the important joint sets are spread all over the slope as observed on

1 the DEM- and they have infinite persistence and (c) big stepped-path failures are possible. The presence  
2 and intersection of persistent joints that kinematically permit the detachment of rocks from the slope face in  
3 every cell of the DEM in reality has a very low probability. This is why these volumes correspond to rare  
4 events with low susceptibility of failure and their distribution may differ from the one for the usually  
5 observed volumes.

6 Larger rock mass volumes than those calculated with this procedure might be possible for slopes with one  
7 predominant and continuous discontinuity set and with scarcity of discontinuities intersecting it, but this  
8 case is not discussed here. This procedure is not recommendable for the size distribution of volumes  
9 smaller than  $100 \text{ m}^3$  because these volumes might be underestimated as they are not easily detectable by  
10 visual observation of the orthophotos.

11 Its application to Forat Negre indicated potentially unstable rock masses of the order of  $50000 \text{ m}^3$  and  
12  $15000 \text{ m}^3$ , for cubic and prismatic volumes respectively, but as explained with low susceptibility to failure.  
13 The fitting of the calculated data for cubic and prismatic volumes greater than  $100 \text{ m}^3$  by a power-law,  
14 indicated an approximate exponent of -0.5. This exponent is smaller than the one assessed by Santana et al.  
15 (2012) for rockfall scars, as it additionally considers the possibility of stepped-path failures. This value is  
16 suggested to be used for the size distribution of big rockfall volumes in the study-site although the volume  
17 may be overestimated because only one failure event is considered for each basal discontinuity surface.

18 It is necessary to emphasise that this work provides information on the potential unstable volumes on rocky  
19 slopes. However for the evaluation of the instability it is necessary to perform further investigation (for  
20 example using limit-equilibrium analysis) and also taking into account the cohesion and friction -based  
21 resistances and the effect of triggering factors.

22 Using the second procedure, it is possible to calculate the size distribution of the in-situ rock blocks using  
23 point cloud data from a Terrestrial Laser Scanner. To minimise errors due to shadowing or occlusion a  
24 DEM obtained by photogrammetry can be used to complement TLS data.

25 The results are very sensitive to the selection of a representative area that is used as the sample window for  
26 the spacing measurements. Visual validation of the area of the sample window and of its representativity  
27 for the entire slope is suggested, if possible.

28 The effect of persistence is different for the PRSD (section 2.3) and the IBSD (section 2.4). When referring  
29 to the PRSD for which the stability or instability are checked at every cell of the DEM, when two or more  
30 cells are found to be unstable they are summed up to give the total unstable mass. This practically means  
31 that big unstable rock masses involve two or more joints of the same set but at different levels in their  
32 interior. Thus the higher the persistence, the higher the presence of joints along the slope and the bigger are  
33 the volumes that might be formed. Instead for IBSD the effect of the persistence is different. As the rock  
34 blocks are defined by just two successive joints of the same set, no joints are included in the interior of the  
35 rock blocks and joints of higher persistence present more frequent intersections and define smaller blocks.

1 The application of the second procedure to the study-site indicated a correlation between the persistence of  
2 the joints and the maximum formed in-situ rock block volumes. The difference between the spacings of the  
3 expected equivalent prismatic volumes for the two extreme cases of infinite discontinuities (theoretical  
4 case) and finite discontinuities (considering only the visible trace length at each plan) is of one order of  
5 magnitude. Comparison of the calculated size distributions for the three volume types V1 to V3 (formed by  
6 the three discontinuity intersections) with the observed data showed that for the study-site which is  
7 intensely fractured, evaluating the persistence only by the discontinuities visible trace length at each plane  
8 is an assumption that provides overestimated volumes, thus is conservative. Instead, the in-situ block  
9 distribution, IBSD, which was observed on the slope face, is better fitted by the calculated in-situ block  
10 distributions for the theoretical case of infinite persistence of the discontinuities. This observation indicates  
11 that in the study area the discontinuities have a very high persistence.

12 The size distribution of the in-situ rock blocks IBSD at the source for the considered discontinuity  
13 intersection and persistence assumptions can be well fitted by a power-law relation with an exponent -1.3,  
14 when the respective exponent for the observed volumes is very close to this value and equal to -1.4. This  
15 indicates that the rock block size distribution presents a certain statistical character which is related to the  
16 network of the discontinuity sets in the slope, as resulting from the process of its structural formation. The  
17 exponent -0.9 found by Santana et al. (2012) for the rockfall scars at the study-site indicated that the latter  
18 in most cases are composed by various in situ-blocks.

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