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Comparing kinematically detachable rock masses and rockfall scar volumes

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Abstract. In rockfall prone areas the evaluation of the risk due to worst case scenarios requires the establishment of maximum thresholds for the expected rockfall volumes. The magnitude of such instabilities is often related to the properties of the jointed rock mass, with the characteristics of the existing unfavorably dipping joint sets playing a major role. The study-site here is the chute of Forat Negre in Andorra. The size distribution of the missing volumes from the scars was calculated using terrestrial laser scanner point cloud data and reaches up to few thousands of m³. On the other hand, the application of Markland criteria on a Digital Elevation Model of the zone indicated the kinematically detachable rock masses to be up to tens of thousands of m³. As the size of the scar areas does not indicate the occurrence of such events in the past, the effect of the joint persistence as assumed for the two analyses is discussed here. The areas of the exposed joint surfaces belonging to each discontinuity set are obtained and their use as a measure of the relative persistence of each set is proposed. The average and median length of the sets F3 and F5 (sliding planes) are found to be similar to the average and median spacing of the intersecting set F7 (tension crack), suggesting that the F7 set exerts a control over the persistence of the former ones.

1. Introduction

The rockfall hazard assessment for worst-case scenarios requires the establishment of maximum thresholds for the expected rockfall volumes in an area. The magnitude of such instabilities is related to the properties of the jointed rock mass, with the characteristics of the existing unfavorably dipping joint sets often playing a major role as planes of detachment of the rock mass from the slope face, although not always failures follow the predominant geological structure.

We have been working at a study-site next to the urban area of Santa Coloma, in Andorra, in order to determine the possibility of large rockfall events. Its special interest lies in the intense rockfall activity, posing a threat to buildings, infrastructure and persons at the adjacent built area. Important funds have been invested by the Government of Andorra for the installation of highly dissipative steel fences to retain and decelerate falling blocks. However, a residual risk still remains [1] which is attributed to rock blocks that are not retained by the protective fences, due to excessive energy or bouncing height. The residual risk should additionally include some potential worst case scenarios for rockfalls with a volume of higher order of magnitude than the one commonly observed.

To evaluate the potential of such scenarios and the respective magnitude, we focus on the slope face and the structural characteristics of the jointed rock mass. To this purpose the results from two types of analysis are discussed.
The first analysis [2] aimed at measuring the dimensions of the scars produced by past rockfalls, in order to obtain information on the volume distribution of previous events. The measuring was realized by means of a point cloud obtained with a Terrestrial Laser Scanner, TLS.

The second analysis [3] was performed to detect kinematically detachable rock masses on a Digital Elevation model, DEM, applying the Markland criteria [4] at each cell. The joining of adjacent cells on the DEM, where the same unfavourable discontinuities outcrop, represents unstable zones. The distribution of the potential rockfall volumes in these zones was calculated.

The results from these analyses are compared. Although with the second analysis potential rockfalls of up to some tens of thousands of m³ are assessed, there are no indications of such events in the slope face. Actually, maximum scar volumes from the first analysis only reach a few thousands of m³. This suggests the existence of a local factor limiting the mass that can be detached from the slope face.

The characteristics of the discontinuity sets are focused on. The considered sets are those that, intersecting each other, they bound the potentially unstable rock masses and/or form the scar walls. The studied characteristics are the discontinuity persistence and spacing of the different joint sets and the relations between them. Bringing this data into evidence, we discuss the use of the dimensions of the scars and of the kinetically detachable rock masses on the slope surface calculated at [2] and [3] respectively, as an input for the indirect measurement of the joint persistence.

This work forms part of an on-going investigation for the detection of potential large rock masses at the study-site.

![Figure 1. The slope above the town of Santa Coloma and the chute of Forat Negre.](image)

2. Study site
The chute of Forat Negre (figure 1) is one of the several active rockfall source areas situated at the slope next to the town of Santa Coloma in Andorra, belonging to the Eastern Pyrenees. It is a steep V
shaped couloir formed in the Southern slope of the Enclar peak (2383m), Santa Coloma wall, and it is composed of graniodiorite rock. The couloir extends from 990 m to about 1300 m a.s.l. The rock mass is highly fractured.

The rockfall activity at the Santa Coloma wall is high with an average frequency of 1 event every 2 years. In the last decades (since the 1960’s) the maximum recorded rockfall events reached the volume of 150 m$^3$ (April, 2008) in the chute of Forat Negre and of 1000 m$^3$ in its neighborhood (Tartera de la Pica, April 1969). The average annual rainfall precipitation is of 1071.9 mm. A direct relation with the rainfall precipitations that might trigger a rockfall has not been established so far. Nevertheless the freeze-thaw weathering process might also play a major role for the rock mass detachment from the slope face.

3. Rockfall scar volumes

The work of [2] aimed at the calculation of the size distribution of past rockfalls, using TLS data, as an alternative to the historical records and reconstructed series. The calculated size distribution represents the volumes of the rockfall masses that have been detached from the slope face in the past leaving a scar bounded by discontinuities. The procedure is based on the assumption that stepped failures sliding over parallel discontinuity surfaces spaced more than 0.2 m did not occur and that each scar on the slope face corresponds at least to an event. This would give an initial estimation of the maximum detached rockfall volume.

A prerequisite for the application of the methodology is the definition of the principal discontinuity sets in the rock mass. Here, the discontinuity sets have been detected following a semi-automatic procedure in which planes are fitted at selected points of the point cloud that fulfil given coplanarity conditions, to form point classes (30 point classes were indentified). The resultant point classes were then merged into 7 main discontinuity sets, based on the scores of a matrix that indicates the percentage of co-existence of these classes on identified discontinuity surfaces both on the point cloud and photos.

Rockfall scars mostly have prismatic shapes, which are formed by the intersection of 4 joint sets. The sets F3 and F5 alternate in the formation of sliding (basal) planes. They are intersected by F1 and F7 which play the role of tension crack (figure 2) although the former may also form rock wedges but less frequently. Table 1 shows the dip direction and dip angle of these sets.

<table>
<thead>
<tr>
<th>Table 1. Dip direction and dip angle of the discontinuity sets that contribute to the formation of scars.</th>
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<tbody>
<tr>
<td>Dip direction ($^\circ$)</td>
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<tr>
<td>F1</td>
</tr>
<tr>
<td>F3</td>
</tr>
<tr>
<td>F5</td>
</tr>
<tr>
<td>F7</td>
</tr>
</tbody>
</table>

To measure the size distribution of the missing volume from the scars, the points of the point cloud belonging to each one of the four sets were isolated and planes were adjusted to them. These planes correspond to the exposed surfaces of the slope face. Afterwards, their areas were measured as well as their maximum width (along the strike) and length (along the dip direction). The areas of F3 and F5 (basal planes of the scars) were well fitted by a Log-Pearson III distribution. The scar heights are the intersections of the tension cracks F1 and F7. To identify them the distribution of the maximum widths and lengths of F1 and F7 were compared, looking for similarities. The lengths of the F1 and F7 were found to have the same distribution and must correspond to the scar heights. The heights were well fitted by the General Extreme Value distribution. Eventually, the size distribution of the scars was calculated past a Monte Carlo simulation by the multiplication of the scar areas with the scar heights.
The results are shown in figure 3. The maximum scar volumes that have been identified using this method are of the order of some thousands of m$^3$.

**Figure 2.** The intersection of the discontinuity sets F3 and F5 (sliding planes) with F5 and F7.

**Figure 3.** Size distribution of the missing volume from the scars [2].
For the evaluation of the results the fundamental assumption of this procedure should be taken into consideration which is that every scar corresponds, at least, to a detachment event from the rock mass. Hence these results may be interpreted as giving a first estimation of the maximum rockfall volumes. However, this excludes the possibility of larger volumes involving several (stepped) basal surfaces, which cannot be fully disregarded with the available information.

4. Kinematically detachable rock masses
Alternatively, for the evaluation of the size distribution of the kinematically detachable rock masses a Digital Elevation Model DEM derived from a topographical map at 1:5,000 scale was used [3]. The DEM at its raster format has a 1m x 1m cell and covers the entire V zone of the chute of Forat Negre.

The detection of potentially unstable volumes consists in identifying on the DEM large kinematically detachable rock masses, by checking compliance with the Markland criteria [4] at every cell of it. In particular, the discontinuity sets F3 and F5, matching the basal planes of the previous paragraph, were checked against two criteria indicating instability: (i) slope angle>joint dip and (i) slope orientation=dip direction±20º. The cells that fulfilled these conditions were marked on the DEM and adjacent cells were joined to form wider areas A, indicating the zones where a rockfall is possible due to the presence of these unfavourably dipping discontinuities (figure 4).

These zones were afterwards superposed on orthophotos to visually verify the zones of the kinematically detachable rock masses and, also, to delineate smaller masses inside the big ones corresponding to smaller detachments. The most extensive zones can be seen in figure 5. The calculation of the volume of the detachable masses was then simplified, assuming either cubic or prismatic shape of the detachable rock masses, with one side equal to the surface of the area A. For the equivalent prismatic volumes the length L of the joint is equal to half of the height of the cubic volumes. The volumes for cubic and prismatic shape were calculated as $V=A^{3/2}$ and $V=0.5*A^{3/2}$, accordingly. The procedure was repeated separately for F3 and F5. Figure 6 shows the size distribution of the volumes summing up the results for both sets.

For the application of this procedure the presence of the discontinuities F3 or F5 at every cell of the DEM is a prerequisite. Infinite persistence of the joints is implied.

The maximum volumes here are of the order of 50,000 and 25,000 m$^3$ for cubic and prismatic volumes accordingly. The largest basal area was estimated at 1,361 m$^2$. 

![Figure 4. Check of DEM raster cells against compliance with Markland instability criteria and joining of adjacent cells to form wider unstable zones [3]](image-url)
Figure 5. Indicative zones where a rockfall is possible given the presence of continuous unfavourably dipping discontinuities superposed on the orthophoto of the study-site.

Figure 6. Size distribution of the kinematically detachable rock masses, for cubic (rhombus) and prisms (triangles) volumes.
5. Comparison of scar volumes with kinematically detachable rock masses

5.1. Conceptual and methodological differences of the two analyses

The calculated maximum volumes based on one hand on the missing scar volumes (of some hundreds up to few thousands of m$^3$) and on the other on the kinematically detachable rock masses (of some tens thousands of m$^3$) present differences of one order of magnitude, being smaller in the first case. This is mainly attributed to the differences of the basic assumptions of the two methodologies.

The calculation of the scar volumes assumes the part of the discontinuities that after a rockfall event remained exposed on the face of the slope. Thus the extent of the discontinuity surface that is implicated in the detachment of the rock mass from the slope face is determined by the scar edges and is limited. In contrast, for the detection of the kinematically detachable rock masses, almost infinite persistence of the discontinuities is assumed. Therefore, the extent of the discontinuity surface that is involved in the detachment due to simultaneous or gradual detachment of blocks is larger (figure 7). Hence the formation of large sliding planes up to 1361 m$^2$ is permitted wherever the instability criteria are fulfilled. Nevertheless such large-extent sliding planes are not observed in situ.

In the light of this evidence the persistence and spacing of the discontinuities are investigated, in order to interpret the limitation in the maximum volume observed in field.

![Figure 7. Formation of large sliding planes through the gradual detachment of blocks along the existing discontinuities (the discontinuities inside the rock mass are drawn with dashed line). The simultaneous detachment of all blocks (large unique failure) would give the same result as well.](image)

5.2. Effect of persistence and spacing on exposed surface areas and rockfall volumes

To measure the spacing of the discontinuity sets, the planes defined at [2] as the exposed discontinuity surfaces on the slope face, were used. The spacing distributions were calculated manually measuring the perpendicular distances between successive planes using the software Rhinoceros (254, 34, 104 and 162 measurements for F1, F3, F5 and F7, respectively). These distributions are seen in figure 8. It can be observed that the joint sets are highly present, with spacings of few meters. It is worth noting that in the detachment of the rock masses, F7 that mostly plays the role of the tension crack, has larger spacings than F3 and F5 (basal planes). The obtained average and median spacings are shown in table 2.

Following the same procedure as described at section 3, the length (along the dip) of the scar edges was also calculated for each set. It was calculated automatically as the maximum edge distance along the dip of a plane. Table 2 summarizes the results for the maximum areas, average and median lengths.
Table 2. Measured areas, lengths and spacings of the discontinuity sets.

<table>
<thead>
<tr>
<th></th>
<th>F1</th>
<th>F3</th>
<th>F5</th>
<th>F7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max spacing (m)</td>
<td>8.09</td>
<td>6.35</td>
<td>4.11</td>
<td>5.60</td>
</tr>
<tr>
<td>Average spacing (m)</td>
<td>2.11</td>
<td>1.84</td>
<td>0.76</td>
<td>1.22</td>
</tr>
<tr>
<td>Median spacing (m)</td>
<td>1.63</td>
<td>1.22</td>
<td>0.53</td>
<td>1.00</td>
</tr>
<tr>
<td>Max area (m²)</td>
<td>121</td>
<td>213</td>
<td>144</td>
<td>236</td>
</tr>
<tr>
<td>Max length (m)</td>
<td>19.85</td>
<td>19.14</td>
<td>14.65</td>
<td>27.08</td>
</tr>
<tr>
<td>Average length (m)</td>
<td>0.96</td>
<td>1.19</td>
<td>0.99</td>
<td>1.45</td>
</tr>
<tr>
<td>Median length (m)</td>
<td>0.76</td>
<td>0.89</td>
<td>0.73</td>
<td>1.04</td>
</tr>
</tbody>
</table>

The maximum areas of the exposed surfaces on the scars are those of F7 and F3, of 236 and 213 m² respectively. They are followed by the areas of F5 and F1 with 144 and 121 m² accordingly. This sorting is consistent with the observations in situ on the exposed surfaces per discontinuity set.

If the sets F3 or F5 had very high to infinite persistence some large basal planes as those delineated in figure 7 would exist. Nevertheless the size of the observed basal planes of the scars is...
limited. This subsequently implies a limitation on the persistence of discontinuities F3 and F5 due to their intersection with F7 that restricts the detachment of large rockfalls. Additionally, the average and median lengths of F3 and F5 (table 2 and figure 9) are of the same order of magnitude as the spacing of F7. These observations suggest that F7 exerts a control over the length of F3 and F5 and in consequence over the expected rockfall volumes, probably disrupting them as depicted at figure 10.

![Figure 10. Similar spacing of F3 and F7 indicate that the former is disrupted by the latter.](image)

The maximum measured length of F3 and F5 (19.14 m and 14.65 m respectively) is one order of magnitude higher than the spacing of F7. To interpret the formation of basal planes with that length, the breakage of small rock bridges of intact rock connecting disrupted discontinuities is assumed.

![Figure 11. In the yellow circle large exposed surfaces of the discontinuity set F7.](image)
To check the afore-mentioned interpretations, rockfall failures have been observed in situ. The areas belonging to the F7 set are predominant (figure 11). These areas of up to few thousands of m², correspond to the largest calculated scar areas, and likely have been formed through the mechanism described in Figure 7. Figure 12 additionally shows a scar where the length of F3 is longer than the spacing of F7. In accordance with the interpretation made here, this scar has been produced as a stepped-path failure with the rock mass sliding over parallel discontinuity surfaces with a maximum distance of 20 cm between them. As verified on the photo this failure involves locally the breakage of small bridges.

![Figure 12](image12.png)

**Figure 12.** A scar with a large basal plane (F3) which is marked by red colour, might be produced as a stepped-path failure after the breakage of small rock bridges, marked with blue colour. The local breakage of the bridges is presented schematically in the lower right hand corner.

6. Conclusions
The results of two analyses for the determination of rockfall volumes are discussed. The first analysis [2] provided the missing volumes corresponding to the rockfall scars and the second one [3] the kinematically detachable rockfall masses according to Markland instability criteria. The obtained results indicate a difference of one order of magnitude between the two maximum calculated volumes, which are greater in the second case. The difference is attributed to the basic assumptions of the two procedures: oppositely to the first analysis, the second one assumes joints of very large to almost infinite persistence.

Based on the geometry of the rockfall scars, the calculation of the area of the exposed surfaces has been possible for each discontinuity set at the study site, the chute of Forat Negre in
Andorra. The discontinuity set F7, acting as tension crack, forms the maximum areas on the slope face (236 m²), followed by the maximum areas of F3 (213 m²) that is the principal sliding basal plane.

As in situ observations do not indicate rockfall failures of the order of the calculated kinematically detachable rockfall masses, the persistence of the discontinuity sets was investigated and indicated to have an effect on it. The smaller size of the observed basal planes was interpreted as a limitation in the persistence of discontinuities F3 and F5, when they intersect with F7. The similar average and median lengths of F3 and F5 with the spacings of F7 (1 m approximately) suggest that F7 exerts a control over the length of F3 and F5 and in consequence over the expected rockfall volumes, probably displacing joints belonging to F3 and F5.

In the scars where the maximum length of F3 and F5 (19.14 m and 14.65 m respectively) is higher than the spacing of F7, the formation of the basal planes can be explained by the breakage of small intact rock bridges.

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