Documenting rock mass failure with UAV during an emergency phase: Castell de Mur case study.

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Abstract

The understanding of the conditioning factors and of the mechanisms involved in rockfalls are requirements for a successful risk assessment and for the prevention of future events. In that respect, the detailed documentation of past event may contribute to this goal. This communication presents methodologies based on UAV surveys to collect detailed documentation of a rock failure as fast as possible to allow the opening of the affected road. The Castell de Mur rock mass failure was a catastrophic mass movement involving around 18,000 m³ and causing 2 fatalities. We use this case to show the possibilities of immediate UAV surveys to create products and models to characterize and document a rock mass failure. The photogrammetric products (orthophoto, Digital Elevation Model, 3D Point cloud and 3D texturized mesh) are used to characterize the rock failure obtaining: high-resolution topographic maps; the block size distribution of fragments in the deposit; the total mobilized volume estimated; the distribution of rock bridges from scar image analysis; and finally, the identification of the involved joint sets and interpretation of the failure mechanism. These products may be used to characterize the failure and to identify the key features for subsequent stability analysis. The realization of the UAV flight has allowed us to collect detailed information about the failure scar and the rockfall debris that would otherwise have been lost after the clean-up of the site and implementation of the remedial works.
1. Introduction

Landslide hazard assessment uses the available information to estimate where future landslides may occur. This task requires the understanding of the instability mechanisms and of the predisposing conditions. An important piece of information may be obtained from the analysis of former events (DOMODIS, 2002). However, features that describe the events can be short-lived. This happens especially when the landslide event affects infrastructures or built areas. Then, the authorities want to start the recovery tasks, clean up the site, and proceed with the remedial works as soon as possible. Under such circumstances a fast documentation process is indispensable in order to avoid that significant information could be lost.

2. Castell de Mur failure

On April 16th, 2018, a massive rock failure buried the road LV-9124, near the village of Castell de Mur, in the Pallars Jussà county, Central-Eastern Pyrenees, Spain. A car was impacted by the rock blocks, causing 2 fatalities. The event occurred after a wet season that ended with 70 mm of precipitation in 4 days. The failure involved a cliff with a height of 18 m high, leaving an 85 m long scar. The rock blocks reached a distance of 100 m and intercepted a stretch of 112 m of road. Figure 1 is the first aerial image obtained with the drone showing the scar and the area affected by the rock blocks. The failure of Castell de Mur affected a bioclastic limestone formation (Cenozoic, Paleogene) interbedded with claystone layers, the latter showing higher erosion rates than the limestone, thus creating rock overhangs that extend between 3 and 10 meters under the cliff. This geomorphic feature favored the settlement of populations during the last centuries taking advantage of the rock shelters, building walls to use it as animal poultry or houses. Figure 2 is a picture taken before the cliff failure. In the picture it can be observed a small hermitage built under the cliff (Figure 2). In the same picture, several blocks can be identified at the base of the cliff associated to previous rockfall events.

Figure 1. Aerial picture of the Castell de Mur failure.
Our research group collaborated with the emergency services in order to identify possible unstable rock volumes in the cliff that could endanger the rescue team and helping in the location of the buried vehicle. We present the data collected, processed and generated in the field, as well as the results of the treatment and analysis carried out during the next days. This communication discusses the potential of UAV surveys to document a large rock mass failure and to generate products for the subsequent analysis of the structural and kinematical features, under emergency conditions. The photogrammetric products (orthophoto, Digital Elevation Model, 3D Point cloud and 3D texturized mesh) allow the characterization of the rock failure obtaining: high-resolution map of the event; the block size distribution of fragments in the deposit; the volume involved, as well as from a 3D reconstruction of the detached mass; the analysis of the scar in terms of joints persistence and presence of rock bridges; and finally, the identification of the joint sets involved in the failure.

Figure 2. Picture before the 2018 failure showing a hermitage under the cliff and rock fragments from previous rockfalls. (Source: http://habitantesdelanada.blogspot.com/).
3. UAV survey

A DJI Inspire 2 drone (UAV, Uncrewed Aerial Vehicle) equipped with the camera X5S was used for photogrammetric purposes as well as for real time observations. The drone was manually piloted during the first flights, using an iPad to display the real time images in order to check the stability conditions of the scar and identify possible unstable rock blocks, focusing on the presence and extent of open cracks.

The flight plan (track in yellow in Figure 3) was designed before going to the field in order to obtain a regular acquisition of pictures to be used in a digital photogrammetry reconstruction.

![Figure 3. Flight plan programmed for regular pictures acquisition.](image)

The flight plan was designed using the “Litchi” web application and based on the previous LIDAR data of the zone available from the Geological and Cartographic Institute of Catalonia (ICGC). The flight altitude was variable, adapting the flight course to the terrain topography in order to maintain the same distance between the camera and the terrain to obtain a homogeneous Ground Sample Distance (GSD) for the whole deposit. We design a doubled flight plan with perpendicular directions in order to obtain the maximum angles of point of view to avoid occlusions by huge blocks.
The camera X5S was used, with a sensor of 5280x3956 pixels and 17.3 mm x 13 mm of real dimensions, and a focal length of 15 mm. We planned the flight at a height of 40 m, obtaining an estimated ground sample distance (GSD) of 0.8 cm/px. The overlapping of pictures within the line of sight was fixed at 75%, planning the drone speed at 3.5 m/s, and taking pictures every 3 seconds. The overlap between lines was defined at 75%, resulting in a distance between lines of 30 meters and 2.9 km of accumulated flight distance. The whole flight was executable in 20 minutes.

Under normal conditions, the flight plan should be optimized in terms of reduction of pictures overlapping and executing the flight with the line courses parallel to the terrain contour lines to avoid change of height and minimize the battery consumption. As it was an emergency, we decide to execute a flight plan with more pictures and points of view than the strictly necessary to avoid missing points of view and loose information. During the programmed flight, 700 pictures were taken.

Another manual flight was carried out in order to obtain both frontal and oblique pictures of the scar and the cliff in order to generate a full 3D reconstruction of the failure setting.

4. Photogrammetric processing

The photogrammetric processing allow the generation of a 3D point cloud, a 3D texturized mesh, a 1cm/px orthophoto and a Digital Elevation Model (DEM) with a 7 cm/px resolution.

The software Agisoft Photoscan was used to generate the 3D point cloud reconstruction. In this case, the main objective was the generation of a high resolution orthophoto in the minimum time as possible in the field. For this reason, we proceed to create a sparse dense cloud using only the GPS coordinates of the pictures to reference de model, 40.000 Tie point and 4.000 key points, and then, a dense point cloud was created in “Low” mode. A “Low” mesh with 50.000 faces was created to be used to project the pictures obtaining the final orthophoto (Figure 4) at 1 cm/px to be shared and studied by the emergency services.

The orthophoto obtained allows the definition of the deposit boundaries, as well as the retrogression of the cliff perimeter (Figure 4).

To study the failure in detail, we start creating a new dense point cloud with more than 17·10^6 points. We use 10 points from the previous LIDAR data of the ICGC to allow georeferencing the model with more accuracy than using only the GPS metadata of the pictures.
Using the 3D point cloud as the main reconstruction of the failure geometry, we start classifying the point cloud in: ground (brown in Figure 4), vegetation (green), blocks in the deposit (orange), overhangs (purple), buildings (red) and rock face above overhangs (blue). This step is necessary to create a Digital Elevation Model (DEM) free of vegetation.

We used the “ground classify” tool in the software Agisoft Photoscan, with the criteria of a cell size of 100 meters to ensure that ground points will appear inside each cell. The other two parameters for ground classification are: the maximum angle, that defines the maximum slope angle that will be considered ground, adjusted at 40º; and the maximum height, that controls the maximum distance in vertical direction of points that will not be considered ground, adjusted at 20 cm.
The results are the points classified as ground and the named “low points” that are points that have other points in the same planimetric coordinates but with different altitude, like the terrain under a tree or under rock. The “low points” identified in the classify ground tool typically correspond to overhangs of the cliff face. We manually selected and classify the rest of the points that are not classified as ground, which correspond to vegetation, buildings, or the steeper parts of the cliff that are rock face above overhangs.

Blocks in the deposit that generate a relief higher than 20 cm or with faces with a slope higher than 40º are not classified as ground, and then, it is also easy to select all of them and classify these points as blocks. The results, is a point cloud classified that can be used to generate the different cartographic or representation products in order to characterize the scenario (Figure 5).

![Figure 5. 3D point cloud classified.](image)

The point cloud with points classified as ground, blocks in the deposit, and rock above overhangs, was used to create a mesh and eventually, a Digital Elevation Model (DEM), from which the vegetation is filtered. The DEM was used to delineate the contour lines using a GIS algorithm. The contour lines reproduce the shape of the block in the deposit and are not affected by the vegetation due to the classification of the point cloud. A pixel size of 7 cm/px is obtained in the DEM generated. We used a GIS software to overlap both the DEM generated and the contour lines to the orthophoto, and thus define the failure setting (Figure 6).
5. Deposit block size distribution

Fragmentation of rock blocks during the failure and propagation is a phenomenon that affects runout as well as the impact energies (Locat et al 2006, Corominas et al, 2019). The studies about fragmentation in rock failures needs determining the block size distribution of the fragments in the deposit, named also Fragments or Rockfall Block Size Distribution (RBSD) (Spreafico et al 2017, Ruiz-Carulla et al 2015 and 2019). Based on the 1 cm/px orthophoto, the deposited blocks may be manual delimited as shown in the Figure 7.

![Digital Elevation Model and the derived contour lines, overlaid with the Orthophoto.](image)

Figure 6. Digital Elevation Model and the derived contour lines, overlaid with the Orthophoto.

The RBSD in terms of cumulative number of blocks versus the block area is obtained using the GIS polygon area function, obtaining the areas list of the 1400 blocks manually delimited (Figure 8).

Alternatively, image analysis methods using the software Image J allow the automatic delimitation of the blocks and calculation of the areas. The obtained RBSD using the Image J analysis may vary in function of the color threshold selected to define the blocks boundaries. Figure 8 shows also a RBSD obtained using the Image J analysis, being the best agreement between the manual and the automatic measures for the five biggest blocks.

The manual delimitation of the blocks based on photointerpretation allow identify and draw overlapped blocks, which otherwise would appear as a single block. For sure, more small
fragments can be manually delimited, as well as different color threshold may be used in the automatic delimitation to better define the smallest blocks.

Figure 7. Deposited blocks manually delimited.

Figure 8. Block size distribution of the deposited blocks based on manual delimitation and based on automatic image analysis.
6. Total volume estimation

The total failure volume is a descriptor used to characterize and classify mass movements. The volume involved may be estimated by measuring the scar dimensions, or by comparing the geometry before and after the failure or trying to reconstruct the volume mobilized. Then, the geometry and morphology of the cliff before and after the failure have to be interpreted, analyzed and described using 2D, 2.5D and 3D representations.

We carried out three different volumes estimation: a) the comparisons between the DEM before and after the failure; b) the comparison between the 3D point clouds before and after the failure; and c) the 3D mesh volume reconstruction based also in the point clouds before and after the failure. The pre-failure DEM and airborne LIDAR point cloud are available from the ICGC public repository. The post-failure DEM and point cloud are the ones obtained from the UAV surveys.

The generation of a 3D texturized mesh with the whole point cloud allow create a render from the same point of view of old pictures of the site (Figure 9). The comparison between the old picture (Figure 9 up), and the render of the 3D texturized model (Figure 9 down) allow the identification of the detached rock volume. Some characteristic elements are used to facilitate the comparison of the images, like a karstic erosion (blue circle in Figure 9) and an old masonry wall (orange lines in Figure 9), and also used to transpose the delineated scar (red line in Figure 9) from the post-failure image to the pre-failure image. The hermitage was destroyed by the rock failure.

Figure 10 (up) shows the map difference using the DEM pre and post failure. Then, the comparison is carried out directly in Z direction. The volume calculated (also in Z direction) is 11972 m$^3$ for the positive values (deposit) and 11139 m$^3$ for the negative values (failure zone).

As the points cloud from the pre-failure LIDAR have distance between scan lines of 2 meters, we decide to create a mesh with these points in order to obtain a more continuous surface. Then, a cloud to mesh distance (C2M) was calculated using the software CloudCompare (Girardeau-Montaut 2006). Figure 10 (down) and Figure 11 show the resultant distances obtained. The distances are measured in the euclidian direction between the mesh and the point cloud. However, the volume is calculated in Z direction using a GIS volume algorithm (Figure 10 down), obtaining 12426 m$^3$ for the positive values (deposit) and 7430 m$^3$ for the negative values (failure zone).

Part of the detached volume rested in place, producing volumetric errors in both cases, using Z direction for the volume estimation.
Figure 9. Comparison before and after the failure. Up: Picture of the cliff before failure. Down: 3D texturized mesh.
Figure 10. Differences map from the comparison of DEMs (up) and from the cloud to mesh (C2M) comparison.
In order to avoid these errors, a 3D mesh reconstruction may be used: the already created mesh from the LIDAR point cloud pre-failure and another mesh created with the point cloud post-failure from the UAV. Then, a 3D closed object may be created by Boolean operation between the two 3D mesh. Figure 12 shows the 3D reconstruction obtained. As the depth of the rock overhang is not fully known, different scenarios are considered, obtaining a volume estimation between 16000 and 18000 m$^3$. 

Figure 11. Cloud to mesh distance results in 3D view.

Figure 12. 3D reconstruction of the detached volume.
Based on the reconstructed 3D model and the interpretation of the cliff basal geometry and its vicinity, a profile is generated showing the detached volume and the deposit of fragments (Figure 12). The profile shows the deposited blocks on the slope and the buried road.

![Profile Diagram]

Figure 13. Profile obtained before and after the failure.

7. Failure mechanism

The failure mechanism was interpreted as a combination of planar sliding and toppling movement due to two factors: the erosion of the base of the cliff; and the propagation of a tension crack in the back of the rock cliff (Figure 14).

Finally, the failure was probably triggered by water infiltration in the tension crack during the rainfall episode.

![Failure Mechanism Diagram]

Figure 14. Evolution of the cliff and the onset of the failure.
The point cloud from the scar was used to create a mesh and a frontal orthophoto. The orthophoto was used to quantify the persistence of the joints in the tension crack. The spectral signature tool in ArcGIS is used to classify the pixels identified as either rock bridge or joint surface. Rock bridges display grey colors related to the rock matrix of the bioclastic limestone. The existing joints exhibit groundwater flow features, such as oxidations and calcium carbonate precipitates (Figure 15).

A total of 1555 m² of the scar surface is calculated, with 995 m² of preexisting joints and 560 m² of rock bridges, whose strength has to be overcome to produce the failure.

Normal vectors from surfaces outcropping within the rear scarp were extracted from the point cloud and then colored using CloudCompare according to the respective dip and dip direction. The plugins qFacets (FastMarching) and the Compass tool allowed to adjust planes (as facets) and define joints manually. Figure 16 shows the point cloud cropped in the scar area with surfaces colored with real color (Figure 16, up), and colored by dip direction (Figure 16, down).

Joint sets were plotted in stereograms and both planar sliding and toppling (kinematic tests) were identified as the mechanism responsible for the failure. Figure 17 shows the stereographic plot of the main joint sets identified using the point cloud of the scarp, with the critical zone for the toppling failure based on the Goodman criteria.

Figure 15. Frontal orthophotos of the scar. Up: original color; Down: classified as rock bridges and opened joints.
Figure 16. Point cloud of the scar. Up: real color. Down: Colored by dip direction.

Figure 17. Stereographic representation of the joints sets identified and the critical zone for toppling failure by Goodman criteria.
8. Conclusion

Detailed documentation of landslides is indispensable to improve the knowledge and the comprehension of the instability mechanism. The documentation of the slope failure should be acquired soon after the occurrence of the event in order to avoid the disappearance of critical features of the deposit and/or the source area during the rescue and restoration works. In this communication we presented the data of the Castell de Mur rock failure collected with UAV flights. The flight was carried out in less than an hour. The presented case example shows the products generated in order to document the event: the 1cm/px orthophoto, the 7cm/px DEM, the 17·10^6 points cloud and a 3D texturized mesh.

These products allow the characterization of the rock failure in the form of: a high-resolution map of the event, the block size distribution in the deposit, the total volume estimation using different methodologies, the quantification of the rock bridges, as well as the structural identification of the joint sets in order to determine the failure mechanism.

All this geometrical and geostructural data will be used for subsequent stability analysis, which based on the information collected here, will specifically address the contribution of the partially persistent tension crack and the cleft water pressures.

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