3D analysis of a fragmental rockfall

Roger Ruiz-Carulla, Gerard Matas, Jordi Corominas, Nieves Lantada

Roger Ruiz-Carulla
International Centre for Numerical Methods in Engineering CIMNE; Edificio C1, Campus Norte UPC C/ Gran Capitán S/N 08034 Barcelona, Spain
e-mail: roger.ruiz@upc.edu

Gerard Matas, Jordi Corominas and Nieves Lantada
Universitat Politècnica Catalunya – BarcelonaTech; C/ Jordi Girona, 1-3 08034 Barcelona, Spain.

Abstract

Fragmentation in a rockfall event influence the total number of fragments, the mass distribution, and the impact energies and runouts. Then, the probability of impact and hazard characterization should consider fragmentation. A fractal fragmentation model has been proposed in order to reproduce the phenomenon. The Rockfall Fractal Fragmentation Model has been implemented in a 3D rockfall propagation simulator named RockGIS. We present the analysis of a fragmental rockfall that occurred in Mallorca, Spain. Fieldworks are carried out in order to obtain the block size distribution of the rockfall deposit. A 3D terrain model is obtained using UAV surveys and digital photogrammetric techniques. The obtained 3D point cloud is cleaned of vegetation and used to create a Digital Elevation Model (DEM). The fragmentation model parameters and the propagation simulator coefficients have been calibrated to accomplish both, the resultant block size distribution and the runout distance of the blocks. The obtained results show a good reproduction of the fragmental rockfall studied. After the calibration is accomplished, older and future rockfalls in the cliff may be analyzed, considering thousands or single blocks simulations with or without fragmentation.

Keywords

Fragmentation model, propagation model, fragmental rockfall, block size distribution, RockGIS, UAV

1. Introduction

Fragmentation of the rock blocks during the rockfall propagation may control the number of fragments, and then, may control the impact energies, the trajectories, and the runouts as well as the whole characterization of the hazard. A single rock block impact should not be the same as hundreds of impacts against a barrier, a road or a vehicle, instead of being the same total volume. Then, the probability of impact may be adapted to the consideration of a single block that breaks creating hundreds of fragments. Finally, the risk assessment (qualitative or quantitative) may be different considering or not the fragmentation phenomenon and it should be taken into account when the hypothesis of no-fragmentation is considered on the safe side, as it is not true in some scenarios (Corominas et al, 2019).

In order to study the fragmentation phenomenon in rockfalls, we have developed a fragmentation model based on fractal theory (Rockfall Fractal Fragmentation Model, RFFM) that allow the reproduction of the block size distributions measured in inventoried rockfalls (Ruiz-Carulla et al, 2017 and 2019). We also have been developed a 3D propagation simulator for rockfalls named RockGIS with the fragmentation model implemented (Matas et al, 2017), that has already been tested with real fragmentation tests (Matas et al, 2020).

The present communication shows the methodologies that we are using in order to analyze rockfall scenarios. The methodologies combine: a) a high-quality 3D data acquisition using UAV surveys and digital photogrammetric techniques to obtain a 3D scenario model; b) field works inventorying the event by measuring the deposited blocks; c) the calibration of the propagation rockfall simulator including the fragmentation model, allowing to reproduce the block size distribution generated by breakage, as well as adjusting the runouts; and d) the use of the calibrated model to study other older or future rockfall events.

We show the procedures applied in a Jurassic limestone cliff located in the north side of Mallorca, Spain. The rockfall case studied is located in the road Ma-10 between the kilometric points 102 and 103. The case can be located at https://rockdb.upc.edu/. This is a coastal local road with two lanes between the cliff and the sea. We have been focused on a rockfall that occurred on the 11th of September in 2019, involving around five cubic meters. The breakage of the rock blocks generates more than a hundred fragments, some of them reaching the road. After the use of this case to calibrate the model parameters, another case that has been occurred in 2015 may be reinterpreted based on some scenarios simulated.

2. UAV surveys and 3D terrain reconstruction

The UAV (or drones) combined with digital photogrammetric techniques allow the generation of detailed 3D point clouds. A DJI Inspire 2 drone (UAV, Unmanned Aerial Vehicle) equipped with the camera X5S (17.3 x 13 mm sensor, 5280x3956 pixels and 15 mm of focal length) was used for photogrammetric purposes as well as for real-time observations (Fig. 1). This device mount two batteries, and can fly approximately 25 minutes per set of batteries, however, we always plan the automated flights of 18 minutes maximum for security and due to the flight plan estimation doesn’t take into account possible adverse wind conditions.

Fig. 1 Drone used: DJI Inspire 2 with the camera X5S.

The flight plan was designed before going to the field to obtain a regular acquisition of pictures to be used in a digital photogrammetry reconstruction. The flight plan was designed based on the previous LIDAR data of the zone available from the Geographic National Institute (IGN). Due to the steepness of the cliff and the whole scenario, the flight plan was designed combining zenital and obliquus pictures. The flight was programmed using the web-app service Litchi, where the drone altitude, velocity, positions coordinates, and the camera orientation and tilt were defined. We always try to maintain the same distance between the camera (drone) and the terrain to obtain a homogeneous ground pixel size (named Ground Sample Distance).

In order to decide the zone to be reconstructed, we carried out a previous analysis based on the slope and the interpretation of the pre-existing orthophotos to identify possible sources of rockfalls. Figure 2 shows the Digital Elevation Model generated based on the pre-existing airborne LIDAR, colored by the slope. The red dots (Fig.2) are potential sources of rockfalls that we are interested in cover it with the drone flight. The blue polygon in the bottom is the road Ma-10, and the two rose tracks in the road are two protection galleries. The orange and white hexagon on the bottom right side is the point decided for the drone take-off and all the flight plans are programmed from this point. Then, the flight plan has to cover more than 700 meters of road and the whole cliff from an altitude of 150m to the top of the cliff at 550m. We executed three programmed flight plans doing 8 tracks at different altitudes to take obliquus pictures of the cliff. A fourth flight plan was carried out taking zenital pictures for the half-lower part of the cliff, obtaining more images of the road and the galleries.

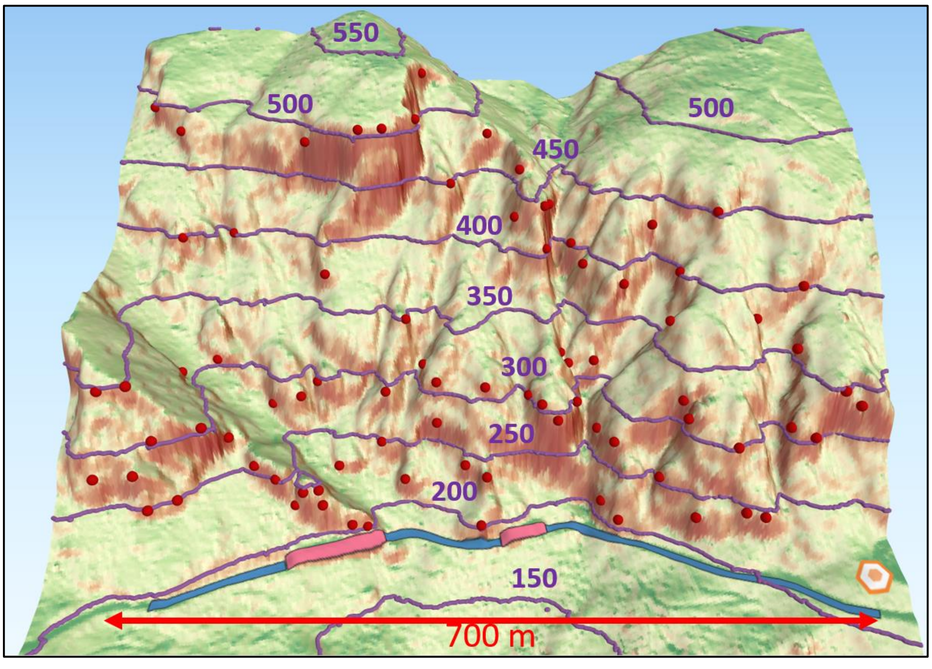

Fig. 2 Digital elevation model of the study area coloured by slope in a 3D view.

We use 542 pictures to create a point cloud with 66.3*10^6 points (Fig.3, up) with the Agisoft Metashape software, covering an area of 0.5 km^2. The mean distance between the drone and the terrain was 150 meters, and the GSD obtained was 3 cm/px. The point cloud was classified to filter the vegetation properly (Fig. 3, down).

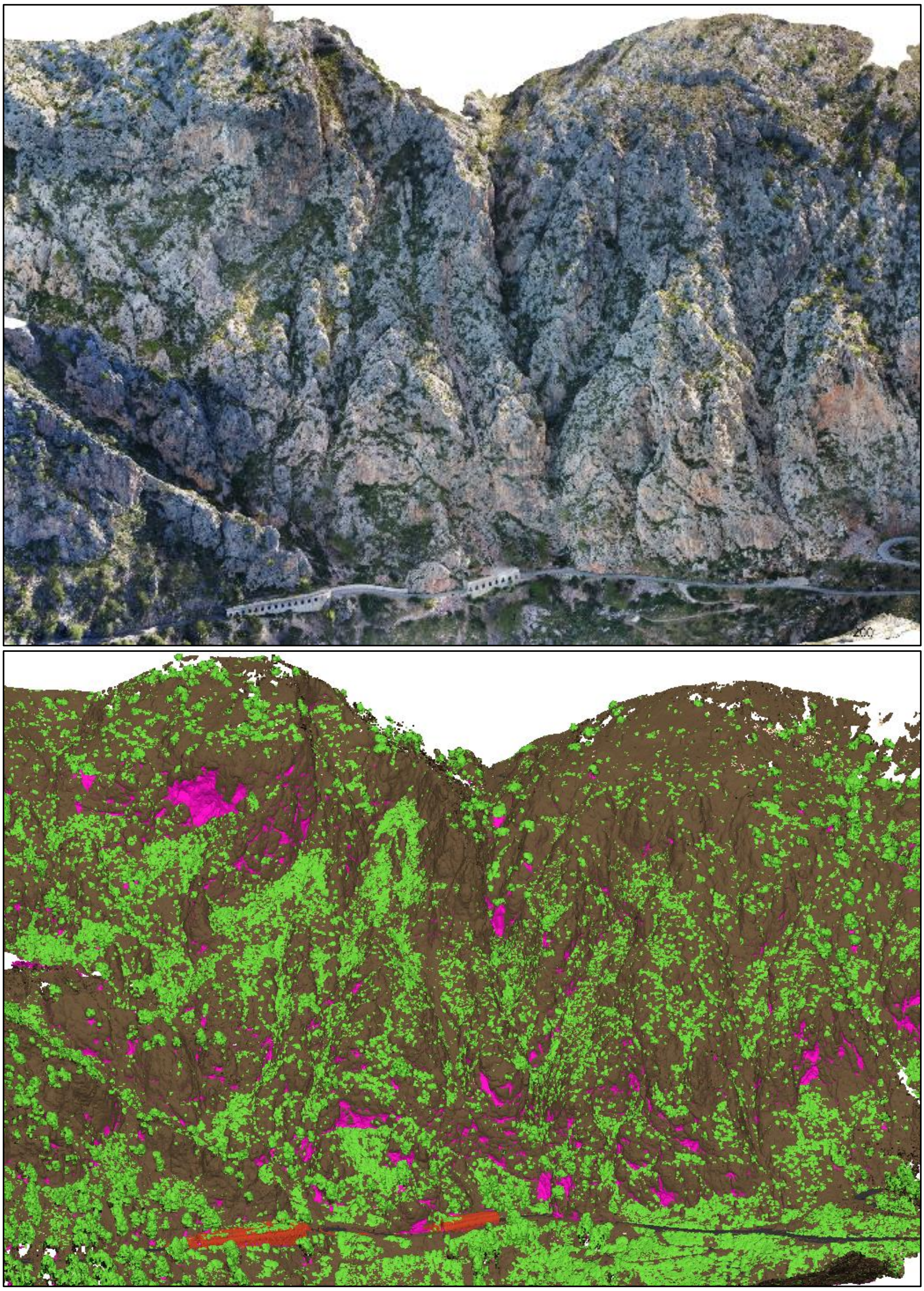

Fig. 3 Point cloud obtained in real color (up) and the point cloud classified (down).

The classification of the point cloud was carried out using first the “Ground points classification” tool, and then the “Classify Points” tool, both integrated into the Agisoft Metashape software. The classification was then manually supervised and corrected in some erroneous classification. Finally, the points identified as “ground” (brown in figure 3, down), “road surface” (grey in figure 3, down) and the “buildings” referring to the protection galleries (red in figure 3, down), are used to create a Digital Elevation Model with 25 cm/px to be used as terrain in the RockGIS rockfall simulator. The points identified as “low points” (purple in figure 3, down), have not been used for the DEM generation due to refers to points with two elevations in the same planimetric coordinates. In this way, the point cloud could also be used in a propagation simulator software based on the 3D point cloud (Noël et al, 2017).

Finally, the point cloud and a 3D texturized mesh was used to characterize the fracture pattern and to identify the potentially unstable volumes for possible cleaning and monitoring purposes, as well as to check the previously potential sources of rockfalls identified (red dots in Fig. 2). On this way, the software Cloud Compare (Girardeau-Montaut 2006), and the plugins qFacets (Dewez et al, 2016) and Compass tool (Thiele et al, 2017) are very useful tools to characterize the joint pattern based on point clouds. The potentially unstable volumes can be defined based on the 3D mesh and correctly delimited using the joint sets that allow the failure based on kinematic stability analysis criteria for planar, wedge or toppling failures (Fig 4).

Fig. 4 Example of a potentially unstable block identified using the joint pattern characterized in the point cloud and extrapolated to cut the 3D mesh.

3. Rockfall Fractal Fragmentation Model (RFFM)

Fragmentation of the rock mass is the reduction in particle size due to an external action. Despite the increasing number of studies on rockfalls, fragmentation as a consequence of the impact on the ground surface is poorly understood. The rock volume detached from a cliff consists of either an individual block or a jointed rock mass. In the latter, the intersection of joints defines individual blocks, which range of sizes is the In-situ Block Size Distribution (IBSD) (Elmouti and Poropat, 2012). As a result of the impact, the rockfall fragments appear scattered along the slope and, as the rockfall volume increases, a more or less continuous debris cover is formed. The range of sizes of the rockfall fragments is the Rockfall Block Size Distribution (RBSD). Here, we use fragmentation as a generic and inclusive term, meaning the division of an initial rock block or rock mass caused by either the breakage of the rock pieces, the disaggregation of joint-determined blocks, or both (Ruiz-Carulla et al. 2017).

We study fragmentation in rockfalls by comparing the IBSD estimated from the detached rock volume versus the final RBSD measured in the deposit (Fig. 5).

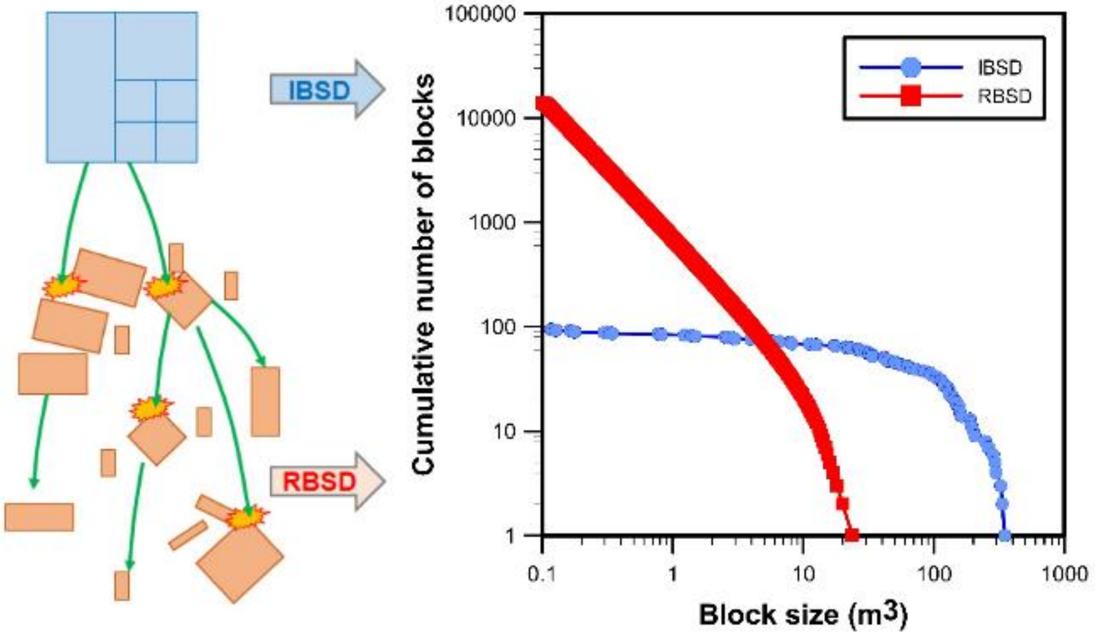

Fig. 5 IBSD and RBSD characterizing the fragmentation process before and after a fragmental rockfall event.

Perfect (1997), described fragmentation as a natural phenomenon that may be characterized using fractals. The performance of the fractal fragmentation model (Ruiz-Carulla et al. 2017), simulate the processes of disaggregation and breakage in rockfalls. The model uses the scale variant equations and the cumulative number of fragments proposed by Perfect (1997) and Ruiz-Carulla et al. (2019).

The use of fractals is related to the same behavior in different scales or orders of magnitudes, also named scale-invariant behavior. This behavior can be identified plotting experimental data in terms of the cumulative number of objects versus their size in a log-log plot and observing a trend line that can be well fitted with a power-law. The exponent of the fitted power-law is also related to the fractal dimension of the system studied. However, the measurement of more than

10.000 fragments in the 7 inventoried rockfalls and real scale fragmentation tests indicate that fragments generated may follow either scale-invariant or variant behavior. The latter is characterized by a change in the proportion between the number of objects and their size. The scale variant behavior implies the modification of the fractal dimensions depending on the objects size. Then, blocks distributions cannot be fitted with a simple power law.

We adapt the equations proposed by Perfect (1997) in order to use an IBSD as a list of volumes as input and work with the initial volume of each block as initiator of a new fragment size distribution. Then, the input of the model may be a single block or a list of volumes. We use the Eq. 1 to generate the new fragments distribution from each initiator block:

$$V_{frag}(n) = V_o \cdot l_{\max} \cdot n^{-1/D}; n = 1, 2 \ldots \infty \qquad [1]$$

The V0 is the volume of each initial block. The use of the cumulative form allows the generation of the fragments one by one. The generated RBSD is obtained increasing n from 1 to infinite. The sequence of volume generation is as follows: first, the largest fragment, and then, the rest of fragments are added, ordered by decreasing sizes, until either the initial block volume is completed or until the fragments become smaller than the threshold defined. The threshold value is established as the minimum volume of the fragments generated (Vmin) that is not measured and checked in the field. The remaining mass below the threshold is computed as fine fraction.

The largest fragment generated after breakage, lmax is defined by the Eq. 2, where q is the probability of survival of the rock block as defined by Perfect (1997). The probability of survival q controls the proportion of the block that survives in combination with a geometric factor b that controls also the size relation between all the fragments generated. In scale-variant, different sizes display different patterns of fragmentation. For instance, the smaller blocks may offer greater resistance to breakage than larger blocks. The increase or decrease of the strength of the rock block as the block size diminishes is simulated with the negative or positive value of r, respectively. For r=0, the scale-variant is equal to the scale-invariant case.

$$l_{max} = q(b^n)^r \qquad [2]$$

Finally, the fractal dimension D is defined by Eq. 3.

$$D = 3 + \frac{\log\left[b^r - q(b^n)^r\right]}{\log\left[b\right]} \qquad [3]$$

Then, the model parameters are the probability of survival q, the geometric factor b, and the scale variant factor r. From there, the largest fragment lmax and the fractal dimension D are calculated by Eqs. 2 and 3. The model can reproduce continuous decreasing size fragment distributions with different fractal behavior from a single block.

4. Trajectory simulation with RockGIS

The Rockfall Fractal Fragmentation Model is implemented in the RockGIS simulator. RockGIS is a 3D trajectory rockfall simulator developed as a GIS-tool using a Digital Elevation Model, and based on a lumped mass model (Matas et al, 2017 and 2020).

In this communication, we have been focused on the reconstruction of a rockfall that occurred on the 11th of September in 2019, involving around five cubic meters single block. The breakage of the rock block generates more than a hundred fragments, some of them reaching the road. We measured the deposited blocks in the field with a tape, obtaining the RBSD (Figure 6, red dots). The source point has been located in the cliff using pictures of the event report from the road surveys. Finally, the impact's energy controls the fragmentation parameters as proposed in Ruiz-Carulla et al (2019). However, the relations between the impact energy and the fragmentation parameters are calibrated for this case to obtain a resultant block size distribution (Figure 6, green dots) that fits the real measurements in the field. The fragmentation can be considered well calibrated in terms of blocks size distribution due to the well agreement with the field measurements.

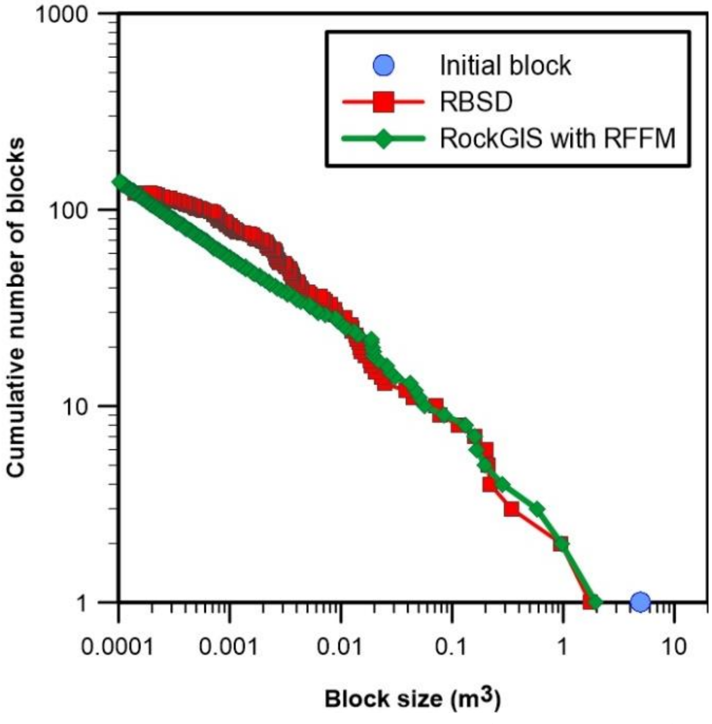

Fig. 6 Block size distrbtuion from the deposit measuremnts (RBSD, red dots) and the results from the trajectory simulator reconstruction (green dots).

However, the reconstruction of the rockfall with the simulators take into account also the runouts and the stopping points. In this way, the calibration uses also the restitution coefficients to reconstruct the whole fragmental rockfall phenomenon in terms of spatial and volumetric characteristics.

Figure 7 shows the trajectories of the fragments obtained from the calibrated simulation, colored by velocity. It can be observed that the initial block is considered as a single block that breaks generating new fragments in the first impact, and then, each independent trajectory breaks again in the second and in the following impacts depending on the impact energy. The stopping points of the fragments simulated fit with the field observations. Then, the calibration is considered well adjusted in both, block size distributions and runout distances.

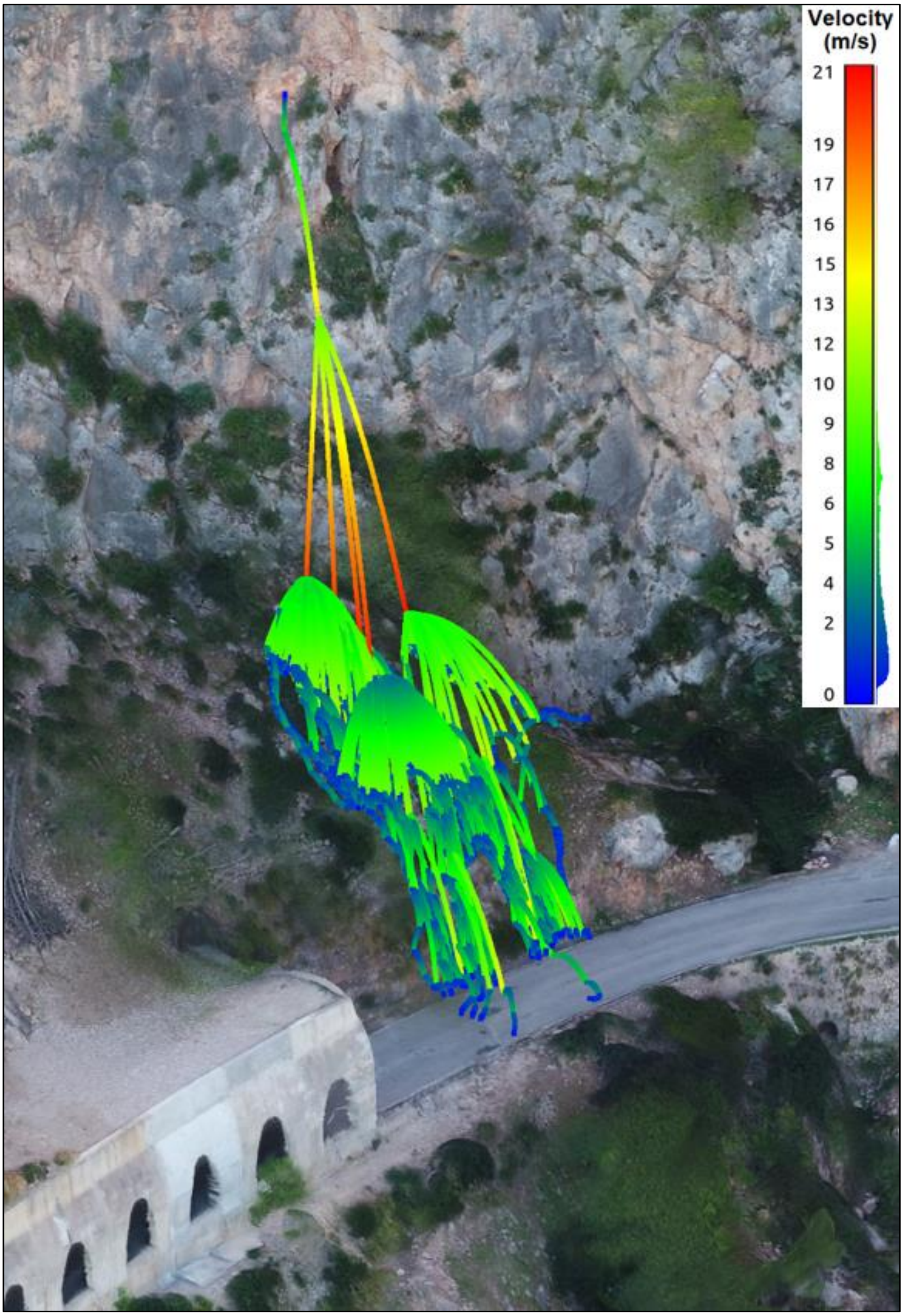

Fig. 7 Results of the rockfall simulated using RockGIS, coloring the trajectories by velocity from 0 to 21 m/s.

5. Discussion

After the calibration of the model parameters for the 2019 rockfall event, the model is ready for other simulations. In 2015, another rockfall event involving 50 m3 detached from 400m of altitude reached a protection gallery destroying a part of it. This event is simulated considering 3 scenarios, Figures 8 a), b) and c).

The scenario a) shows a common procedure running 1000 simulations of a single block of 50 m3 without fragmentation. Most of the trajectories simulated reach and or overpass the road and the protection gallery (Fig. 8 a). However, the actual rockfall event was only one of those simulations. Fig.8 b) shows just one simulation of a single block of 50 m3 without fragmentation. In this case, the block impacts directly on the destroyed part of the protection gallery in 2015. Finally, Fig 8 c) shows the case that better reproduces a fragmental rockfall from our point of view. The simulation shows a single block detached from the cliff of 50 m3 considering fragmentation upon the impacts against the terrain during its propagation. Part of the fragments generated stop before reach the protection gallery creating small deposits along the path. The bigger fragments go further reaching the protection gallery causing a multi-impact effect. The affected area considering fragmentation increase in comparison to the single block simulation without fragmentation, as well as the probability of impact. However, Fig 8 c) shows the results of only one simulation, and then, to get a probabilistic evaluation of the hazard, hundreds of simulations should be run.

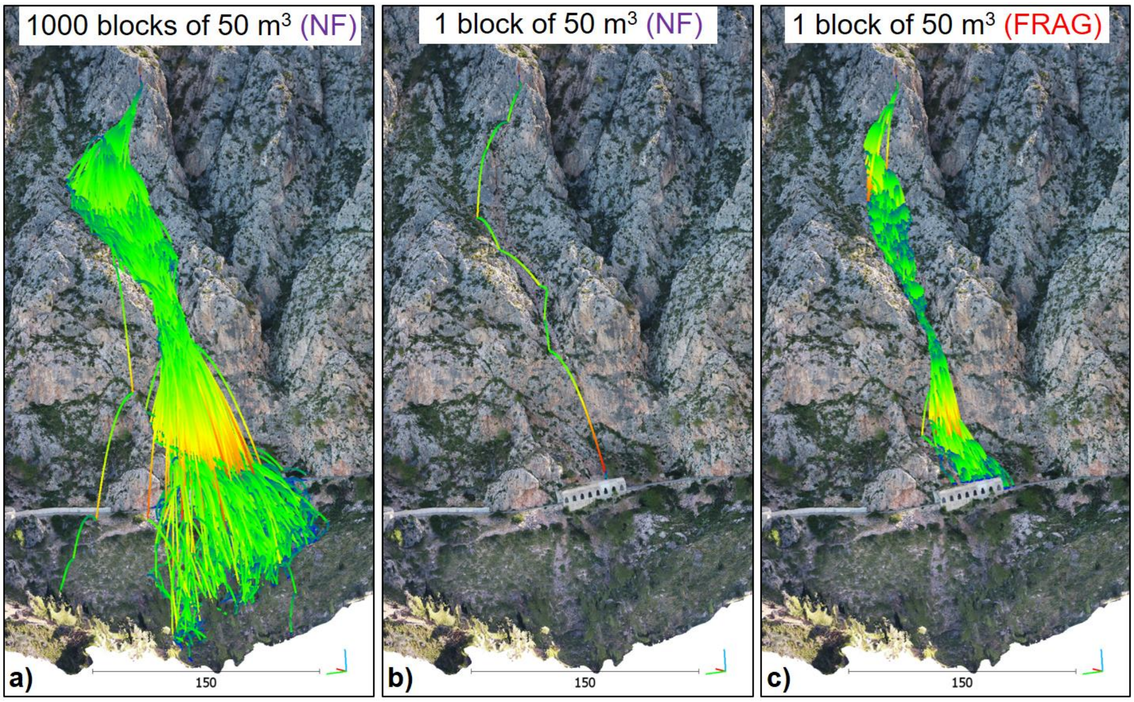

Fig. 8 RockGIS simulations result for 2015 rockfall: a) 1000 simulations without fragmentation, b) one simulation without fragmentation and c) one simulation with fragmentation.

6. Conclusions

This communication shows a methodology to analyze fragmental rockfalls. The use of UAV and digital photogrammetry allow high-quality 3D data to characterize the potentially unstable volumes and to obtain the terrain reconstruction as input for trajectory simulators. At this point, the correct vegetation filtering from the point cloud is necessary to create a useful Digital Elevation Model. Then, the use of our RockGIS simulator with the Rockfall Fractal Fragmentation Model implemented allows the reproduction of the fragmental rockfall behavior in terms of both, block size distributions and runouts. This is an example of fragmentation consideration to take into account working with hazards and risks associated with rockfall. Further analyses and considerations are then needed to define the hazard maps taking into account the fragmentation implications, as well as the implications derived to the fragility curves for multi-impact against structures, roads, vehicles or people.

7. Acknowledgments

This study was supported by the research project RockModels (Ref.BIA2016-75668-P, AEI/FEDER.UE) funded by the Spanish Ministry of Economy and Competitiveness. Acknowledge also, to the local government of Mallorca (Balearic Islands, Spain).

References

Corominas J, Matas G, Ruiz-Carulla R (2019). Quantitative analysis of risk from fragmental rockfalls. Landslides. 16(1): 5-21. DOI: 10.1007/s10346-018-1087-9.

Dewez T Girardeau-Montaut D, Allanic C, Rohmer J (2016) Facets: A Cloud Compare plugin to extract geological planes from unstructured 3D point clouds. International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume XLI-B5, 2016

Elmouti, MK, Poropat GV (2012). A Method to Estimate In Situ Block Size Distribution. Rock Mechanics and Rock Engineering, 45(3): 401-407.

Girardeau-Montaut D (2006) Detection de Changement sur des Données Géométriques 3D, PhD manuscript (french), Signal & Images Processing, Telecom Paris.

Matas G, Lantada N, Corominas J, Gili J.A, Ruiz-Carulla R, Prades A (2017). RockGIS: A GIS-based model for the analysis of fragmentation in rockfalls. Landslides 14(5), 1565-1578. DOI: DOI:10.1007/s10346-017-0818-7.

Matas G, Lantada N, Corominas J, Ruiz-Carulla R, Prades A, Gili JA (2020). Calibration of a rockfall simulator with a fragmentation model in a real scale test. International Symposium on Slope Stability in Open Pit Mining and Civil Engineering. May 2020, Perth (Australia)

Noël F, Wyser E, Jaboyedoff M, Clouthier C, Locat J (2017). Development of a 3D rockfall simulation model for point cloud topography. EGU General Assembly Conference Abstracts.

Perfect E (1997) Fractal models for the fragmentation of rocks and soils: a review. Engineering Geology 48:185-198.

Ruiz-Carulla R. & Corominas J. (2019). Analysis of rockfalls by means of a fractal fragmentation model. Rock Mechanics and Rock Engineering. DOI:10.1007/s00603-019-01987-2.

Ruiz-Carulla R, Corominas J, Mavrouli O (2017). A fractal fragmentation model for rockfalls. Landslides. 14 (3): 875-889. DOI:10.1007/s10346-016-0773-8.

Thiele ST, Grose L, Samsu A, Micklethwaite S, Vollgger SA, Cruden AR (2017). Rapid, semi-automatic fracture and contact mapping for point clouds, images and geophysical data. Solid Earth, 8: 1241-12535.