Comparison of block size distribution in rockfalls

R. Ruiz[1], J. Corominas[1] , O. Mavrouli[1]

[1] *Dept. of Geotechnical Engineering and Geosciences / Technical University of Catalonia (UPC), Barcelona, Spain*

ABSTRACT Rock masses detached as rockfalls usually disintegrate upon impact on the ground surface. The knowledge of the Rockfall Block Size Distribution (RBSD) generated by the propagation of the rockfall mass is required for the analysis of the trajectories of the blocks, the run-out distances, the impact energies, the quantitative assessment of the rockfall hazard and for the understanding of the fragmentation process. We have measured the volume of the blocks detached in 5 rockfall cases, obtaining the corresponding RBSD. The total volume involved in these rockfall events ranges from 2.6 m^3 to 10000 m^3. The obtained RBSD can be well fitted by power laws with exponents ranging from 0.51 to 1.27. The results suggest that these exponents may be related to the height of fall (potential energy) and to the proportion of new fractures generated in the rock mass, among other factors.

1 INTRODUCTION

Evans and Hungr (1993) and Hungr et al. (2014) reserved the term fragmental rockfall, for the events in which the rock fragments move as independent rigid bodies interacting with the ground surface through scattered impacts. They distinguished it from the term rock avalanches in which masses of fragments move in a flow-like way. In fragmental rockfalls, the detached rock mass, which often includes discontinuities, it disaggregates, breaks or both after the first impacts on the ground. The resultant fragments propagate independently downhill. The deposit of a fragmental rockfall includes blocks of different sizes scattered on the ground surface. In the case of large fragmental rockfalls (thousands or tens of thousands of cubic meters) a more or less continuous Young Debris Cover (YDC) can be formed.

Understanding the fragmentation process is fundamental for the analysis of the rockfall hazard (Jaboyedoff et al. 2005; Corominas et al. 2012), since it is a critical input datum for calculating the trajectories and the run-out of the rock fragments, the encounter probability with the elements at risk and the expected impact energies. Run-out analyses performed with the originally detached rock mass volume produce results, which are significantly different from those using individual rock blocks (Okura et al., 2000; Dorren 2003). The initial rock mass may lead to the overestimation of the rockfall kinetic energy and run-out. If the modal or the maximum block fragment size is used instead, the travel distances and the energies obtained are more realistic. However, the frequency and the impact probability are largely underestimated as in reality, the original rock mass splits into a large number of rock fragments, leading to the multiplication of the impact probability by a factor “n” equal to the number of new blocks generated.

An indicator of the fragmentation degree is given by the Rockfall Block Size Distribution (RBSD). Several parameters influence the fragmentation process and the RBSD (Dussauge et al. 2003; Wang & Tonon 2010) namely: the presence of discontinuities in the detached rock mass as well as their persistence, aperture and orientation at the moment of the impact, the impact energy, the rigidity of the ground, the impact angle and the velocity.

2 STUDY CASES

We have measured the volume of the blocks deposited in 5 rockfall cases located in Catalonia, Spain, obtaining the corresponding RBSD. The rockfall volume involved in these events ranges from 2.6 m^3 to 10000 m^3. The rockfall cases represent 5 different scenarios of volume, lithology, height of fall and surface morphology.

To obtain the RBSD, we measured the blocks using a tape, assuming either a rectangular or triangular prismatic shape of the blocks and measuring 3 dimensions of each one. In the case of large fragmental rockfalls, the size distribution in the Young Debris Cover (YDC), is obtained by measuring all the blocks over a certain volume inside sampling plots, and then extrapolating the distribution over the homogenous zone represented by the sampling plot. The definition of the homogeneous zones, the selection of the sampling locations and the extrapolation procedure is described in detail in Ruiz et al. (in press).

The obtained RBSD can be well fitted by power laws with exponents ranging from 0.51 to 1.27.

2.1 Pont de Gulleri rockfall

Pont de Gulleri rockfall took place near Sant Romà de Tavernoles village. The measurement of the accumulated blocks gave a detached rock mass volume of 2.6 m^3, and height of fall of 12 meters (Figure 1 left). The cliff is composed of Cambro-Ordivician schists with a high persistence joint pattern. The fallen blocks are bounded by preexisting joints (Figure 1 right). This allows us to assume that the detached rock mass was disaggregated following the joint pattern. Only one block shows fresh breaks. The block size distribution (RBSD) was obtained by measuring 116 blocks in the deposit, and the curved shape could be related with the In Situ Block Size Distribution (IBSD) (Elmouttie and Poropat 2011) in the cliff. The minimum block volume measured is $1.2*10^{-4}$ m^3, and the maximum is 0.28 m^3.

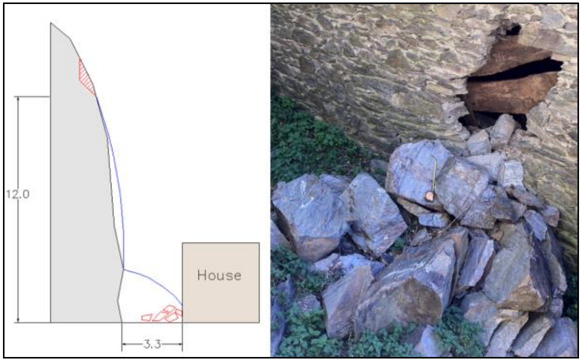

Figure 1. Left: Scheme of the Pont de Gulleri rockfall case (distances in meters). Right: picture of the deposited blocks.

2.2 Lluçà rockfall

In the Lluçà rockfall the detached volume is 10.7 m^3. The rupture mechanism is predominantly toppling caused by differential erosion of the underlying weak rocks (Figure 2). The rock is grey sandstone of Upper Eocene age. The detached mass was a single block bounded by two main fractures filled with roots. The latter might have facilitated their development. The fallen blocks show fresh faces generated by the impact and a lot of fine material associated with the breakage. We measured 77 blocks, with a minimum volume of $6.7*10^{-4}$ m^3 and a maximum volume of 8.47 m^3. The RBSD obtained can be very well fitted by a power law with an exponent of 0.51.

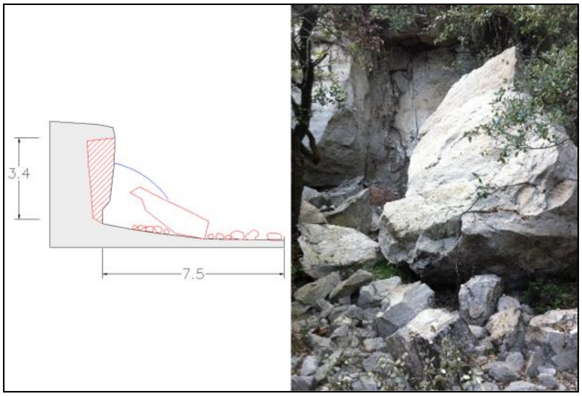

Figure 2. Scheme of the Lluçà rockfall case (distances in meters). The high number of small blocks results from the fragmentation of a large one.

2.3 *Omells rockfall*

Omells rockfall is located in Omells de na Gaia village. It is a small-size rockfall that propagated on a stepped soft ground. The first free fall height is less than 0.8 m, and the block with the maximum run-out stopped by impacting with a wall at 22 meters from the source area (Figure 3). In the lowest part, the blocks trajectories crossed a paved road and damaged a barrier (Figure 4 and Figure 5). The detached rock is a sandstone of Oligonece age. The detached volume of this event is 4.2 m^3. We measured 48 blocks, with a minimum volume of 7*10^{-4} m^3, and a maximum volume of 1.1 m^3. The blocks generated by fragmentation show fresh faces related to the breakage as well as preexisting discontinuities, mostly sedimentary planes.

The fragmentation of the rock mass during the propagation of the rockfall changed the trajectories of the blocks, modifying the impact energies (Figure 5). The RBSD obtained can be very well fitted by a power law with an exponent of 0.53.

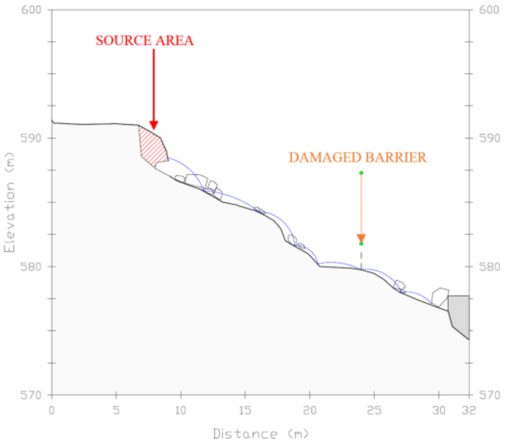

Figure 3. Scheme of the Lluçà rockfall case (distances in meters).

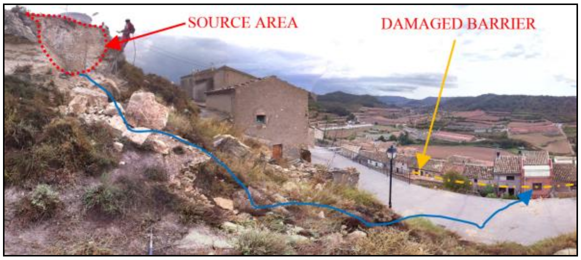

Figure 4. Omells rockfall, with the source area, the trajectories and some of the deposited blocks.

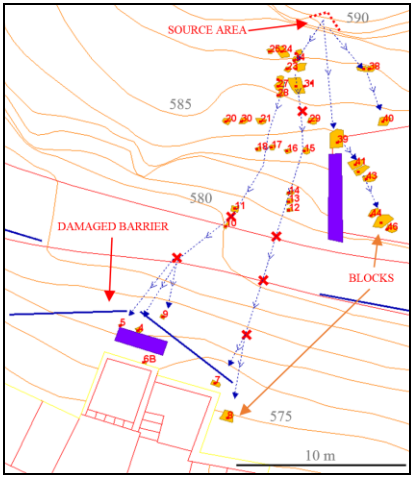

Figure 5. Map of the Omells rockfall case, with the source area, the trajectories, the impacts, the deposited blocks and the damaged barriers.

2.4 *Malanyeu rockfall*

Malanyeu rockfall is a large rockfall, with a total volume detached close to 5000 m^3. The rock is Maastrichtian limestone. The free fall height is less than 10 meters, and the maximum run-out distance is 100 meters, reaching the valley bottom (Figure 6).

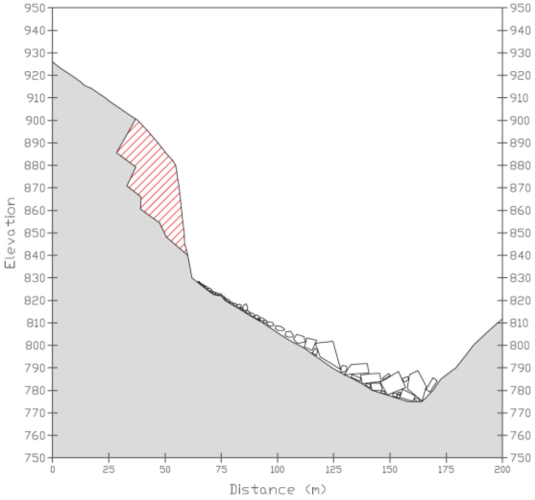

Figure 6. Scheme of the Malanyeu rockfall case.

We measured 2721 blocks, with a minimum volume of 4.2*10^{-5} m^3 and a maximum volume of 445 m^3. The deposit includes 7 blocks greater than 100 m^3, and more than 60 blocks greater than 10m^3.

In this case, the fragmental rockfall generated a more or less continuous Young Debris Cover (YDC) in the upper part of the deposit with a high concentration of small-size blocks (Figure 7 left). To obtain the block size distribution from the YDC, we defined 3 homogenous zones, where block sizes are relatively similar. In each zone, we selected a sampling plot. We measured all the blocks over a certain volume inside it (zone 1: $4.2*10^{-5}$ m^3, zone 2: $1.4*10^{-4}$ m^3 and zone 3: $1.6*10^{-4}$ m^3).

The sampling plots have a square shape, and the area is proportional to the size of the blocks inside (sampling plot in zone 1: 4 m^2, zone 2: 16 m^2 and zone 3: 6.25 m^2). Finally, we extrapolate the block size distribution obtained from the sampling plots to each homogeneous zone. To this end, we used the ratio between the area of the homogenous zone and the area of the sampling plot representative of the zone. See Ruiz et al. (in press), for further details.

The faces of the accumulated blocks are mostly preexisting discontinuities in the rock mass (joints and bedding surfaces). Figure 7 (right) depicts the source area, the boundaries of the homogeneous zones used and the biggest blocks deposited at the lower part of the deposit.

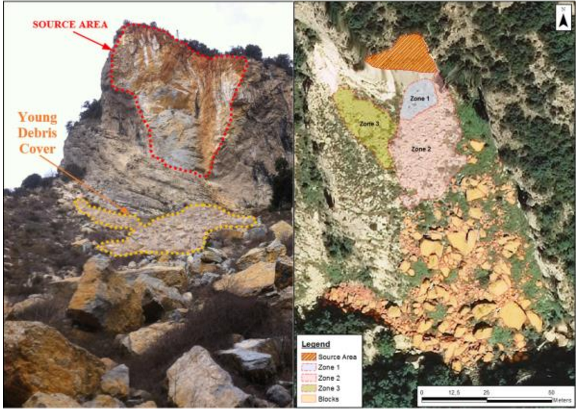

Figure 7. Left: Malanyeu rockfall. Right: Orthophoto map showing the YDC, the blocks and the source area in the Malanyeu rockfall case

This case corresponds to a large fragmental rockfall where the fragmentation is related to both the disaggregation of the rock mass along preexisting discontinuities (joints and bedding planes), and pure breakage. A proof of this is the presence of huge blocks, bounded by preexisting discontinuities in the lower part of the deposit and, on the other side, the blocks of the YDC, generated in the upper part of the slope after the first impacts of the rock mass, showing multiple new faces.

The obtained RBSD can be very well fitted with a power law with an exponent of 0.72.

2.5 Vilanova de Banat rockfall

Vilanova de Banat rockfall is located in Cadi Sierra, in the Eastern Pyrenees. The cliff is made of limestone of Paleocene age. The volume detached is close to 10.000 m^3, based on field measurements and on the reconstruction of the detached mass from a 3D model of the scar generated by photogrammetric technics (Ruiz et al., in press).

The free fall height is 40 m, and the maximum run-out distance is 740 m (Figure 8). The first impacts generate a Young Debris Cover of 30.000 m^2 (Figure 9 left). Three roughly homogenous block sizes zones have been identified: the highest, middle and lowest parts of the YDC. We further divided the highest part in 3 zones, and the lowest part in 2 zones (Figure 9 right). We measured 1252 blocks in 6 sampling plots (one per each defined zone) and 272 as Large Scattered Blocks (LSB). The corners of the sampling plots and each LSB measured were georeferenced with a GPS (Figure 9 right). The extrapolation of the block size obtained from the sampling plots to the homogenous zones is explained in detail in Ruiz et al. (in press). The minimum block volume measured is $1.53*10^{-3}$ m^3 and the maximum block volume is 30.8 m^3.

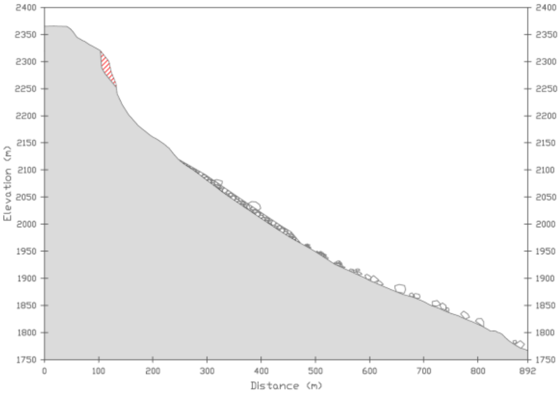

Figure 8. Scheme of the Vilanova de B. rockfall case.

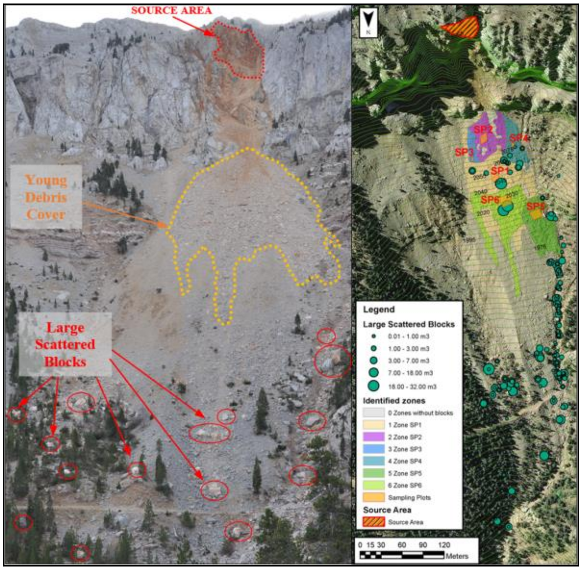

Figure 9. Left: Vilanova de Banat rockfall. Right: Orthophoto map showing the location of the six homogeneous zones of the YDC, samplings plots, the large scattered blocks and the source area in the Vilanova de Banat rockfall case.

We measured 1524 blocks, and after the extrapolation of the data from the sampling plots to all the YDC, we estimated 60.000 blocks in the deposit.

The blocks deposited have an irregular shape, showing fresh faces related to the breakage and some faces defined by the preexisting joints. Field observations suggest that the deposit was mainly originated by breakage. This is confirmed by the large number of small and medium blocks and the predominance of fresh faces in the blocks. The obtained RBSD can be very well fitted with a power law with an exponent of 1.27.

3 RBSD COMPARISON

The obtained RBSD is expected to be related to the predominant fragmentation mechanism of the rock mass during the propagation. The final RBSD depends on the IBSD, the geomechanical characteristics of the rock, the impacts energies, the total volume detached and the morphology and rigidity of the ground. The obtained RBSD based on field measurements are plotted in relative frequency terms (Figure 10), while the main attributes are summarized in Table 1.

The studied cases show different scenarios with specific conditions:

-Pont de Gulleri case is a disaggregation case, with the blocks clearly delimited by preexisting joints.

-Lluçà rockfall is a case with pure breakage. The total volume detached is 10.7 m^3, and the biggest block measures 8.47 m^3.

The 20% of the original mass was broken from the detached block, generating a distribution of blocks that clearly follows a power law.

-Omells rockfall involves a low fall which progresses on a soft and stepped ground, and the rock is very weak. The fragmentation occurs by breakage of the blocks but strongly controlled by the anisotropy of the rock related to the bedding planes. This case is very similar to the Lluçà case.

-The deposit in Malanyeu rockfall shows the influence from the IBSD in the cliff, related with the shape and the volume of the blocks. The fragmentation by breakage is observable mainly in the YDC. The preexisting discontinuities are prevalent features in the faces of the bigger blocks. The low energy (limited fall height) of the rockfall could account for the large number of big unbroken blocks.

-The deposit in Vilanova de Banat rockfall shows more fragmentation by breakage, less big blocks and a high exponent of the fitted power law. Probably, this high degree of fragmentation by breakage is related to the free fall height and to the volume detached, which generate high impact energies at the beginning of the propagation. Furthermore, the IBSD could have an important influence as well.

Table 1. Rockfall cases data.

Rockfall	Exponent of the fitted power law (b)	R^2	Total Volume (m^3)	Free fall height (m)	Lithology
Pont de G.	0.92	0.94	2.6	12	Schist
Lluçà	0.51	0.95	10.7	0.6	Sandstone
Omells	0.53	0.89	4.2	0.8	Sandstone
Malanyeu	0.72	0.98	5000	10	Limestone
Vilanova	1.27	0.95	10000	40	Limestone

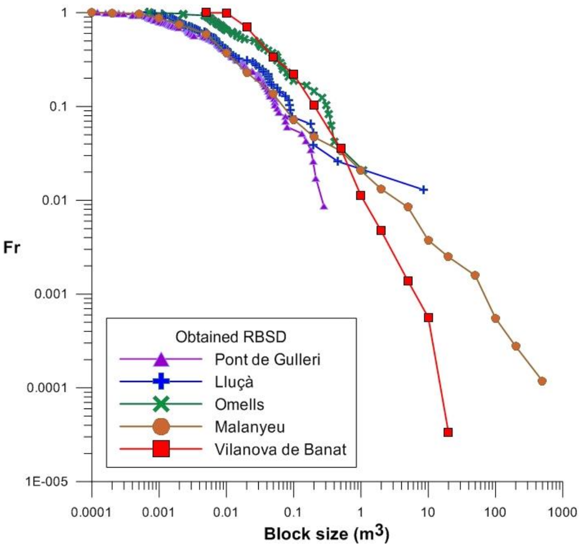

Figure 10. RBSD obtained in relatively frequency versus block size.

4 CONCLUSIONS

We conclude that the exponent of the fitted power laws to the RBSD can be used to characterize the block size distribution generated in a fragmental rockfall, and it may also provide information on the fragmentation phenomenon. The results suggest that these exponents may be related to the height of fall (potential energy) and to the proportion of new fractures generated in the rock mass, among other factors. However, to characterize the fragmentation more information is needed on the IBSD, the total volume detached, the impact energies and the morphology and the rigidity of the ground. The disaggregation of the blocks in the case of Pont de Gulleri rockfall suggests that the obtained RBSD is related with the preexisting joints in the detached rock mass.

The cases of Lluçà and Omells show a very similar behavior, with the difference that in the Omells case, the stepped ground allows more impacts. The Lluçà rockfall has only one impact, allowing the survival of a large block in a low energy scenario.

Malanyeu and Vilanova de Banat cases are large fragmental rockfalls showing different RBSD. The higher value of the exponent of the fitted power law in the case of Vilanova de B. rockfall suggests a degree of fragmentation higher than the Malanyeu case. This is confirmed in the latter location by the accumulation of some very large blocks and by the higher presence of preexisting discontinuities in the faces of deposited blocks.

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