Experimental study on rockfall fragmentation: in situ test design and first results

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ABSTRACT: Fragmentation is a common feature of rockfalls that exerts a strong influence over the trajectories of the generated blocks, the impact energies and the runout. Real scale rockfall tests have traditionally been designed to evaluate the parameters of rockfall motion. In this contribution we present the results of a set of tests carried out in a limestone quarry that will be used to calibrate and support rockfall propagation models. A total of 56 blocks ranging between 0.2 and 4.8 m^3 were dropped from two slope profiles with different morphology and falling height (16.5 and 27.5m total fall). Trajectories of the blocks and velocities were tracked with three high-speed video cameras. Some 43% of the blocks fragmented upon impact with the ground. Most of the blocks were massive limestone although a small percentage displayed a varying amount of finite fissures. The characteristics of the blocks, in particular the size and the Schmidt L hammer rebound were measured before the tests. The results show a lack of correlation between the Schmidt L hammer rebound and the disintegration of the blocks. Finally, it has been observed that the volume (size) distribution of the fragments resulting from the disintegration follow a power law with negative exponents ranging between 0.18 and 0.69. These results are consistent with the observed volume distributions in several natural rockfall events inventoried in limestone environments.

1 INTRODUCTION. THE ROCKRISK PROJECT

Rockfalls are frequent instability processes in road cuts, open pit mines and quarries, and steep slopes and cliffs (Cruden & Varnes 1996). The attitude and persistency of joints within the rock mass define the size of kinematically unstable rock volumes and determine the way the fragmentation of the detached mass occurs as a consequence of its impact with the ground. Knowledge of the size and trajectory of the blocks resulting from fragmentation is critical in determining the vulnerability of buildings and protection structures. The probability of occurrence is also necessary for the Quantitative Risk Assessment, QRA (Fell et al. 2005; Corominas & Mavrouli 2011).

As it is rare to witness a real rockfall event, most methods concentrate on studying the source point and the spread of the debris over the deposit area, both surveyed after a given event (Abellán et al. 2006; Ruiz et al. 2015, 2016).

Several programs are available to model the trajectories, usually considering the individual propagation of blocks. In general, in these models the blocks do not fragment during the runout, while in most real rockfalls the detached mass becomes fragmented during its propagation downhill. The results may significantly differ (Jaboyedoff et al. 2005; Agliardi & Crosta 2003). The current research on fragmentation includes empirical as well as analytical works (Giacomini et al. 2009; Zang et al. 2000; Wang & Tonon 2010).

The R&D project ROCKRISK (2014) is under development to improve our knowledge of the fragmentation processes in the rockfalls and their role in the risk quantification and the prevention of this type of instability. Among other tasks, the project includes the analysis of the fragmentation laws using data collected from recent and/or controlled rockfall events. In this experimental part of the study, several real-scale rock fall tests were carried out. At convenient, restricted locations, a number of rock blocks were released downhill under controlled circumstances. Before, during and after the fall, a variety of parameters and images were recorded. This field work is of paramount importance in capturing the physical bases of the natural process and gathering useful information for adjusting the numerical modelling later.

Thus, we begin this contribution by describing the design of two of these in situ dropping tests (section #2) and the realization of the field work (#3). Then we present the first results (#4) and the work currently under development (#5), and we finish with some concluding remarks.

2 TEST DESIGN AND SITE PREPARATION

In this section we describe the preparation of two real scale rockfall tests that were carried out in an quarry located at Vallirana (Barcelona, Spain), where the lithology of both the slopes and the rock blocks is massive limestone.

After a convenient profile has been selected, during the test a number of rock blocks will be released downhill under controlled circumstances. The design phase consisted of: the exact definition of the profiles; the equipment selection and setup; and the establishment of the procedure to follow in preparing the test, dropping the blocks and measuring the scene, including the safety guidelines.

In Figure 1 the two test sites are presented in sections. TS#1 is a single benched slope, whereas TS#2 is a multiple benched one, but during the test the blocks only reached the second platform. Therefore, for all practical purposes, only two jumps should be considered. The total fall, including the bulldozer blade height, is 16.5 m for TS#1 and 27.5 m for TS#2. These measurements were only approximate at the design stage, being confirmed later at the execution phase.

Figure 2 shows the planned equipment and personnel layout around TS#1 and TS#2 respectively. To define the exclusion area (red pattern in Fig. 2), a 30º aperture angle was staked out from the dropping point. In the vertical plane, a reach angle of 30º was considered. During the execution phase, it was verified that these values were sufficiently safe.

After the design phase, the in situ preparation of the site took about 2 days prior to the rockfall test. A total of 56 massive limestone rock blocks ranging between 0.2 and 4.8 m^3 were prepared for the two

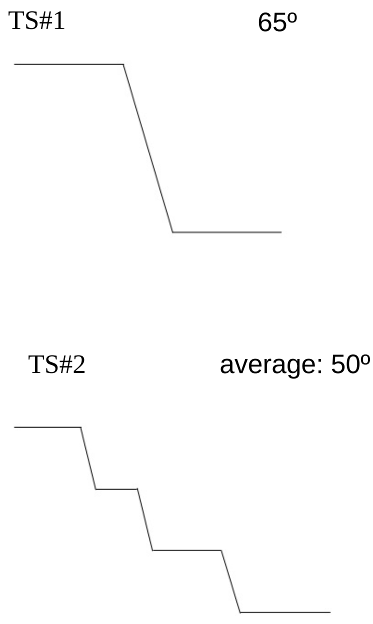

Figure 1. Sections corresponding to Test Site #1 (top) and Test Site #2 (bottom). Each bench is approximately 12-13m high.

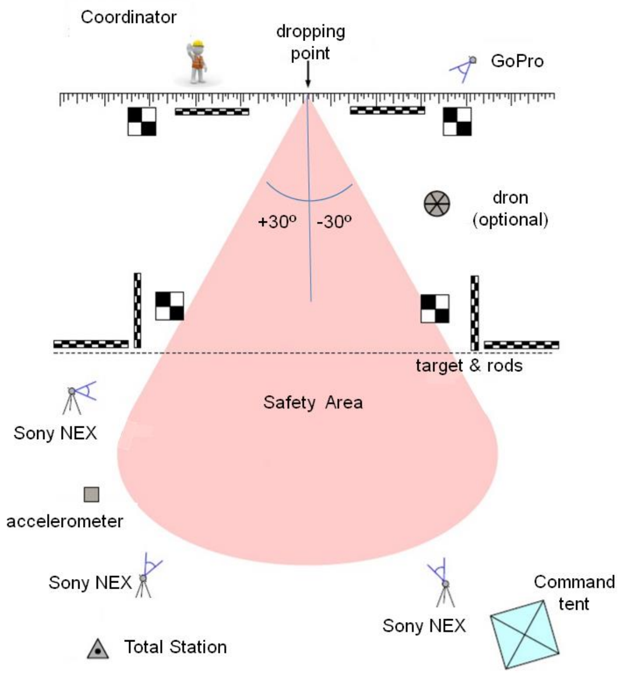

Figure 2. TS#1. Plan view with the planned equipment and personnel layout.

test sites. The characteristics of the blocks, in particular the size, the Schmidt L hammer rebound and the fissuration index (normalized observable fissure length on the block surface) were measured before the start of the tests.

In order to make the blocks more visible during their fall as they rotate and bounce downslope, three major color ‘circles’ were painted on each block (Fig. 3a). The geometry (shape and volume) and the surface texture were recorded with a ‘circular photogrammetric survey’, block per block (Fig. 3b). Encircling the rock block in this way has enabled us to build a 3D model (see #5) and compute the volume, weight and gravity center, among other things.

Figure 3. Preparing the tests.
Top: painting the blocks.
Bottom: detail of the so-called ‘circular photogrammetric survey’

Immediately prior to the test, surveying rods and targets were distributed around the scene (Fig. 4). These items were used as Ground Control Points (GCP) and/or metrical scales in order to georeference all the photographic and video images.

3 DEVELOPMENT OF THE TESTS

After the preparation tasks, everything was ready for the start of the rockfall tests, which were carried out on the 17th (TS#1) and 18th (TS#2) of June, 2015. While the preparation stage required only 2 or 3 people, during the actual tests a minimum of seven people (plus the dozer operator) were necessary to take care of the systems and tasks.

A general view of the TS#1 is presented in Figure 5, with the blocks visible left of the bulldozer that threw them. The reference targets are also clearly observable in the photograph. Figure 6 shows the TS#2 general view.

Figure 4. Targets and surveying rods were deployed around the scene for georeferencing.

Figure 5. TS#1, Oblique aerial view taken with a drone

Figure 6. General view of the multiple benched TS#2

After the installation of all the cameras and systems, a survey of the GCP was carried out with a Leica TM30 reflector-less Total Station (Fig. 6, foreground). This was also an excellent opportunity to perform the first drone (Fig. 7) aerial photogrammetric campaign and capture the full scene prior to any damage. During the test, these two systems were used regularly to position some important features (the final position of the blocks or fragments, impact points, etc). For instance, we decided to fly the drone once every 5 drops in order to capture the

Figure 7. One of the two drones used in the rockfall test

position of the block and the fragments. In addition to the oblique views and rockfall videos, if the drone covers the whole area, orthophotomaps can be produced easily (see section #5).

30 of the blocks were dropped at TS#1 (single bench), then 26 blocks at TS#2 (double benched slope). Each block was dropped after the field coordinator checked that all systems (mainly the cameras and flash) and operators (bulldozer, optionally the drone) were ready and/or safe.

Apart from standard picture or video digital cameras (including two GOPRO Hero4), the propagation of each block was recorded by means of three high-speed (H.S.) video cameras (Sony NEX FS700R) that were set up in convergent lines-of-sight (Fig.2).

As examples of the products we acquired in the field, Figure 8 presents a sequence of 4 frames extracted directly from a HS video. This block did not break, although some chips may have broken off the corners.

In order to characterize the degree and pattern of the fragmentation of the block, after each drop the size of the main resulting pieces of the rock were measured by hand with a tape (Fig. 9). From time to time the lower platform area was cleared with the bulldozer to facilitate the identification of new incoming blocks/fragments.

4 FIRST RESULTS ABOUT FRAGMENTATION

One of the main objectives of the rockfall tests was to improve our knowledge of the fragmentation processes, and it has been successfully achieved. As stated earlier, some 43% of the blocks fragmented upon impact with the ground. The videos allow the identification of the moment of fragmentation and the tracking of the disaggregation of the original block into pieces that carry different energies and velocities (Fig. 10).

Figure 8. TS#1. Series with 4 frames extracted from a frontal view video.

Figure 9. Top: inventory tasks in the lower platform. Bottom: big fragment of #22 surrounded by fractions.

Another result of the process was the pieces and their stopping points. The variability of behavior among the blocks (Fig. 9, 11) is notable but nothing unusual for natural materials.

What can be done is to study the patterns in an aggregated mode, trying to infer the main features of the average behaviour during the fragmentation process. An indicator of the degree of fragmentation is given by the Rockfall Block Size Distribution (RBSD). An explanation on the RBSD and its adjustment can be found in Dussauge et al. (2003), Wang & Tonon (2010) and Ruiz et al. (2015, 2016). It has been proved that the RBSD obtained in the field (natural events that are inventoried afterwards) is consistent with power laws.

The information gathered in our tests is well suited to applying this method that will help us to characterize the registered fragmentation. In Table 1 the exponents (b) of the power law are summarized preliminarily. The fragmented blocks have been grouped in classes according to the number of fragments.

Consequently, we can state that the size distribution of the fragments resulting from the disintegration follows a power law with negative exponents ranging between 0.18 and 0.69, the larger exponents corresponding to the blocks that broke into a greater number of fragments. These results are consistent with the observed volume distributions in several natural rockfall events inventoried in limestone environments (Ruiz et al. 2015, 2016).

Table 1. Exponent of the RBSD

Range of fragments	Power law ‘b’ exponent best fitted to the distribution
1-3	-0.18
4-9	-0.24
10-31	-0.4
32-74	-0.5
75-123	-0.69
All classes together	-0.45

Figure 10. Two frames that contain two fragmentation events. The first one happened in the slope while the second in the lower platform.

Figure 11. TS#1, Detail of the remaining fragments after 5 rock block drops, 3 of them suffered an intense fragmentation.

Regarding the prediction of block breakage, most of the blocks were massive although a small percentage displayed a varying amount of finite fissures, part of them filled with cemented breccia. Some clear candidates for breakage remained unbroken after the drop. When preparing the tests we made systematic measurements of the rebound number measured with the sclerometer known as Schmidt L hammer. Unfortunately, the results showed a lack of correlation between the Schmidt L hammer rebound and the disintegration of the blocks. This was probably due to the fact that the L hammer measurement affects only a small portion of the rock (the centimeters closest to the impact point), which is not enough to represent the average state of the block and its fissuration. The correlation between the fissuration index (normalized observable fissure length on the block surface) and the breakage occurrence is more promising, but the computations are still under implementation.

5 ONGOING POSTPROCESSING WORK

When writing this contribution, part of the huge amount of information gathered during the rockfall tests is still under post-processing.

With the aerial photos taken with the drones, several orthophotomaps (Fig.12) and 3D models (Fig. 13) have been produced. Using the ‘circular photogrammetric survey’ (Fig.3b) we have built 3D models for each block (Fig. 14). VSFM, MESH and Agisoft software have been used for these purposes.

This geometric information (slope, block volume, weight, gravity center) is of paramount importance for the ongoing work dealing with trajectories and fragmentation pattern recognition. The 3D model also helps in further characterization of the block (fissuration index for instance), even if it no longer exists.

Figure 12. TS#1 Orthophotomap generated

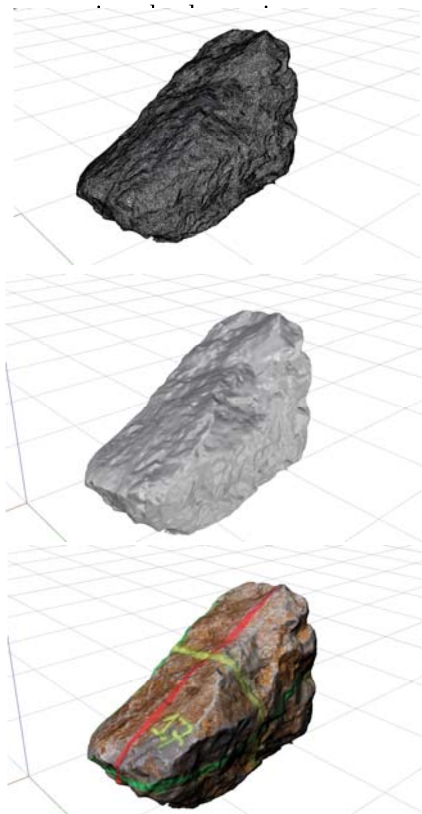

Figure 14. Block 17 3D models: mesh, shaded and texturized color models.

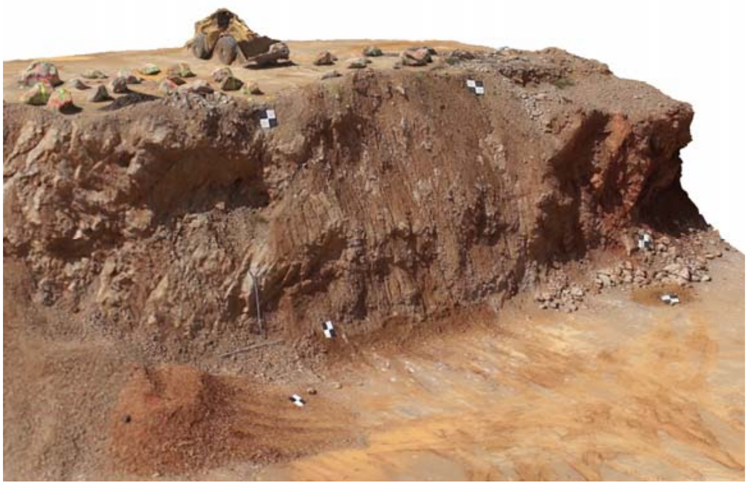

Figure 13. 3D image model corresponding to Test Site #1 (see Fig.5)

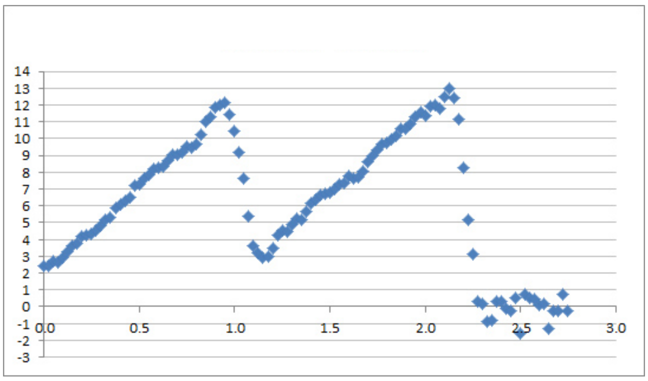

Figure 15. Block 24 velocity profile (m/s) (5-averaged).

Using the video shots, after the image orientation steps the position of the blocks (and fragments) can be triangulated and the velocities and energies computed, filtered and averaged (Fig.15). The velocities at the lower platform impact point range between 12.5 and 15.9m/s for TS#1 and between 13.1 and 16.9m/s for TS#2.

So far, most of these computations have been made with non-automatic methods, frame by frame or with small scripts. After this manual phase, we are currently developing supervised semiautomatic tools for the videotriangulation (Fig. 16).

Figure 16. Trajectory from semi-automatic video-triangulation, block 24, TS#1

6 CONCLUDING REMARKS

In this communication we have presented the results of a set of tests carried out in a limestone quarry. Apart from using them to calibrate rockfall propagation models, we are improving our knowledge of the fragmentation processes during the propagation phase.

The use of new tools such as drones, high speed video cameras and massive photogrammetric software has proved very useful. Playing the drops again later and measuring values that were not planned initially is an advantage. However, to post-process all the raw material, some pieces of adhoc new software must be developed. The data processing has not finished yet.

In the short term, we plan to perform new tests in other lithologies and morphologies, within the frame of the ROCKRISK project.

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