TLS- and inventory-based Magnitude – Frequency relationship for rockfall in Montserrat and Castellfollit de la Roca

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Hazard scenarios are defined by a representative event of a certain magnitude, which corresponds to a frequency of occurrence or annual probability. In rockfall, scenario magnitude is identified by the total volume detached. Therefore, in diffuse hazard assessment it is crucial to fit this relationship magnitude/frequency, called McF, where cumulated frequency is quoted in spatial & temporal terms. Inventories are the classical source of data to deal with this objective. Last decade, TLS or digital photogrammetry monitoring came to offer a complementary approach. The samples obtained by the two methods have a specific coverage and each has its own lack of information that can be compensated together.

1 CASE SITES AND DATA

1.1 Montserrat massif of conglomerate (M)

Montserrat Mountain is an isolated massif formed mainly by layers of conglomerate, and a characteristic relief of rocky walls and needles very attractive for climbing. It is placed at 50 km NW from Barcelona, in Catalonia, NE of Spain. The interest for this case is the rockfall risk on infrastructures and buildings to be managed according to natural and cultural heritage preservation besides the touristic activities. TLS available data cover more than 12 years of surveys in several scanner stations at different altitude and aspect of the mountain slopes (Table 1) (Janeras *et al.*, 2017). The historical and observational inventory has 205 events recorded from 1546 to present, ranging from 0.001 to 2160 m^3.

1.2 Castellfollit de la Roca basaltic cliff (C)

Castellfollit de la Roca is a country-side village placed at 50 km NW from Girona city, in Catalonia. The interest for this case comes from the risk caused by the rocky cliff retreat, since the town is placed at its top. The cliff is formed by columnar basalt of ancient lava flows in this inactive volcanic area, where the whole cliff become a high value landscape heritage. TLS available data cover near 12 years of surveys in 3 scanner stations and points of view of part of the cliff (Table 1) (Abellán *et al.*, 2011). Available inventory data cover 43 years from 1976 to 2018 and recorded 17 events from 1 to 1500 m^3.

Table 1: Collected data with TLS surveys and McF regression.

Sample	Area (hm^2)	Period (years)	No. of surveys	Sampling (hm^2·year)	No. of events	Volume min (m^3)	Volume max (m^3)	A_{st}	B	R^2
M: Degotalls_N+E	3.06	12.56	24	38.42	357	3.0E-04	7.9E+02	0.392	0.527	0.977
M: Monastery	3.57	8.79	23	31.39	162	2.0E-04	4.8E-01	0.097	0.652	0.875
M: Rack railway	1.83	3.36	8	6.15	19	1.6E-03	1.7E-01	0.104	0.656	0.986
M: Collbató Caves	2.32	3.82	7	8.86	21	6.0E-04	1.7E-01	0.180	0.464	0.943
Montserrat_ALL	10.78	7.87		84.82	397	5.0E-03	5.0E+01	0.166	0.640	0.987
C: Upper lava flow	2.40	11.86	5	28.47	194	5.3E-04	6.0E+00	0.333	0.472	0.970
C: Lower Lava flow	0.24	8.53	5	2.05	91	3.1E-04	3.8E+00	1.134	0.534	0.974
Castellfollit_ALL	2.64	11.56		30.52	240	2.0E-03	3.2E+00	0.391	0.490	0.995

The temporal and spatial coverage of each sample can be expressed in hm^2·year, according to the surveyed outcrop surface and the period. The larger a component or another, the more appropriate is the analysis of spatial or temporal variability.

2 MAGNITUDE-FREQUENCY RELATIONSHIP

2.1 Magnitude range

TLS and inventory data cover different volume ranges, according to sampling coverage (in time and space) and systematic detection capabilities. Therefore, the combination of both data allows to reach the maximum representativeness of the McF relation expressed by a potential law for the spatial & temporal cumulated frequency F_{st} for detached volume equal or larger than V_i, with unitary activity A_{st} and distribution coefficient B:

$$F_{st}\,(V \geq V_i) = A_{st} \cdot V_i^{-B} \qquad (1)$$

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Power law fitting corresponds to the assumption of scale-invariant behaviour. Montserrat data suggest that as rockfall mechanism changes, this hypothesis can become wrong, and the fitting can be scale-variant for different volume ranges. Statistical distribution of volume in the lowest limit is clearly affected by the detection capability of each surveying method and the surveying frequency, so the well-known roll-over effect is observed. Similarly, in the upper limit apparent scale-variant effects are observed in highest volumes due to several effects on extreme values recorded in the sampling, certainly limited. To overcome both distortions, different filtering techniques are applied in order to fit the power law for the central part.

2.2 Spatial variability

At massif scale, results of the power laws agree with the values obtained by previous similar work in France (Hantz *et al.*, 2020). Parameter B can be correlated with rock mass quality, where not only fracture density seems relevant, but the intercalation of hard and soft rock layers also could play a role (Table 1). In the same massif and lithology (Figure 1), at outcrop scale both parameters A_{st} and, in some reverse way, B show a fairly large variability that must be analysed more in detail, as it may become relevant for hazard zoning.

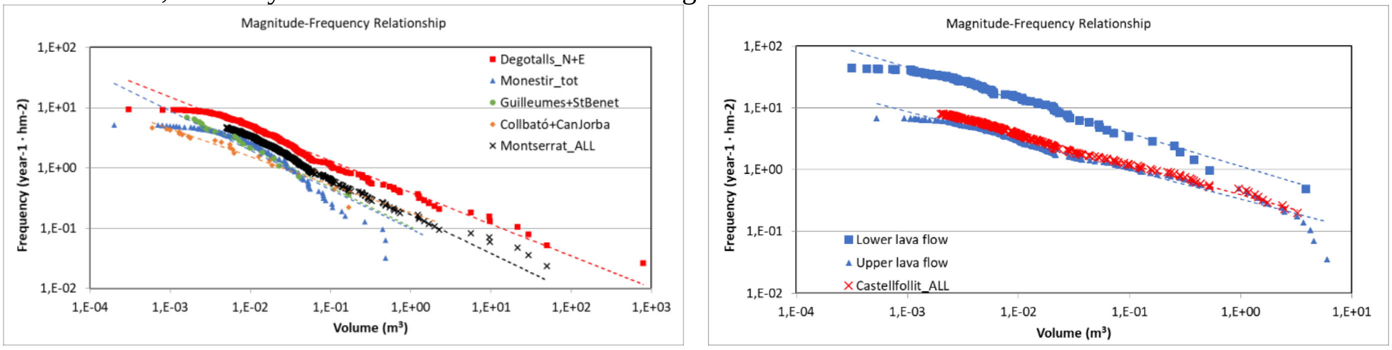

Figure 1: Magnitude – cumulated Frequency power law fitting for different samples in Montserrat (left) and Castellfollit de la Roca (right).

2.3 Temporal variability

As known, hazard is variable in time according to episodes of detaching actions, like rainfall. This rockfall activity along time is reflected to different values of A_{st} & B parameters for each sub-sampling in yearly periods (Figure 2). The effects of stabilization works, progressives rupture episodes and other changes in the wall can be seen reflected in these parameters over time. Also, from this variability is deduced the convenience of five years minimum duration of sampling so as not to be excessively subject to particular periods.

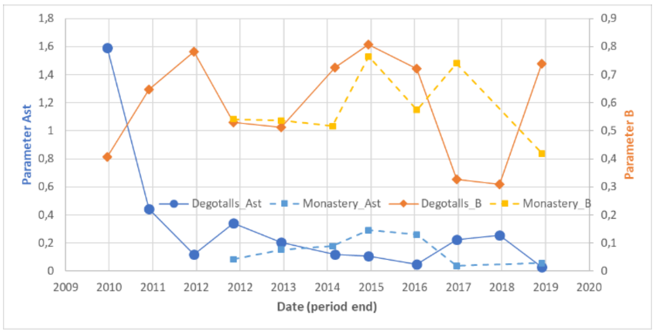

Figure 2: Time variability of A_{st} & B parameters in Montserrat.

CONCLUSION

Rockfall inventory combined with monitoring with TLS allow an adequate hazard of detachment assessment as a basis for quantitative risk analysis, insofar as they allow to define scenarios of a certain magnitude to which to assign an annual probability of occurrence.

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